The Top Forward-Backward Asymmetry at the Tevatron

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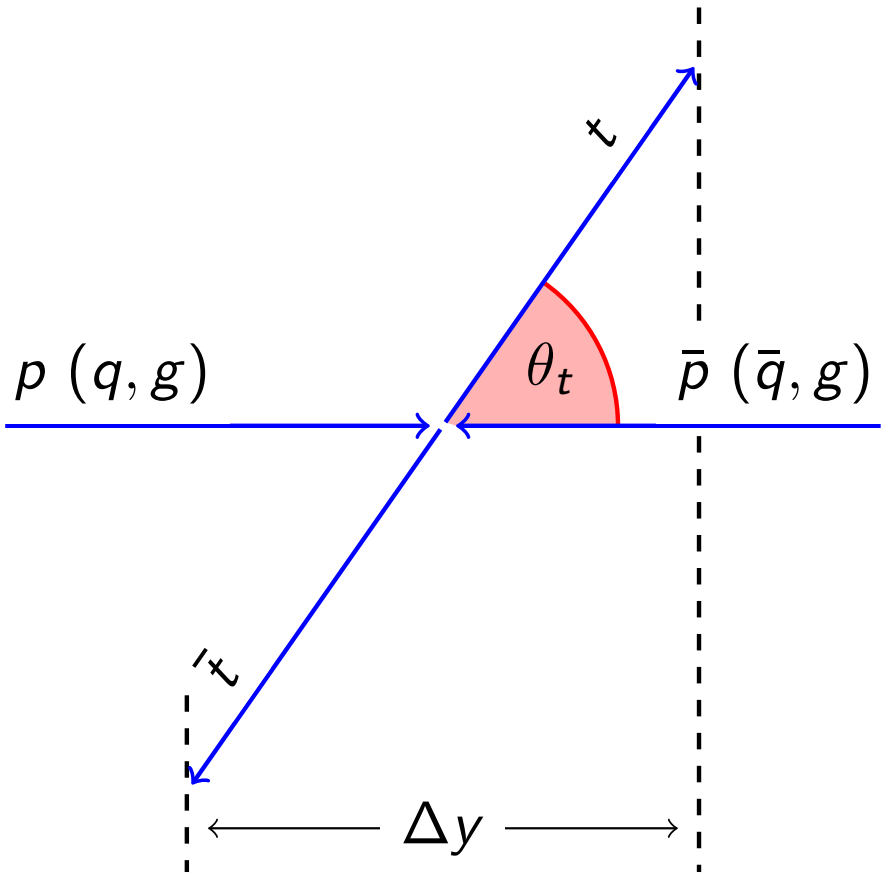
Part I

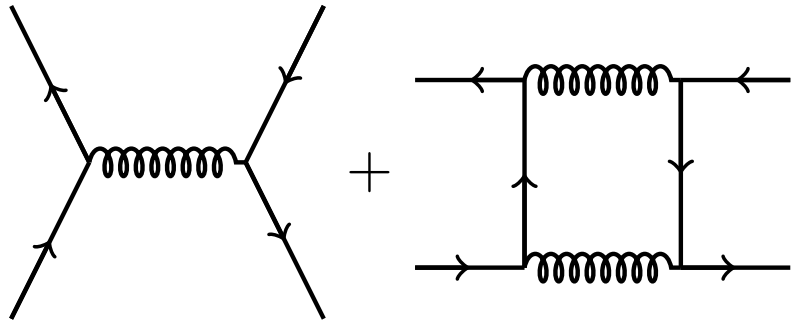
Introduction

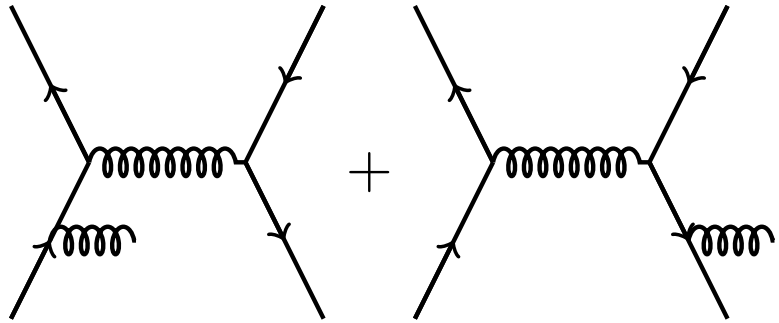
- Discovered in '95 by CDF, DØ
- 40× heavier than bottom
- ∼ mass of caffeine molecule
- Special role in EWSB?
- Enhanced coupling to new physics?
- Characterize top pair production in $p\bar{p}$ collisions via:
  - α_s: strong coupling
  - q^2: energy scale
  - s: spin/polarization
  - θ_t: top production angle



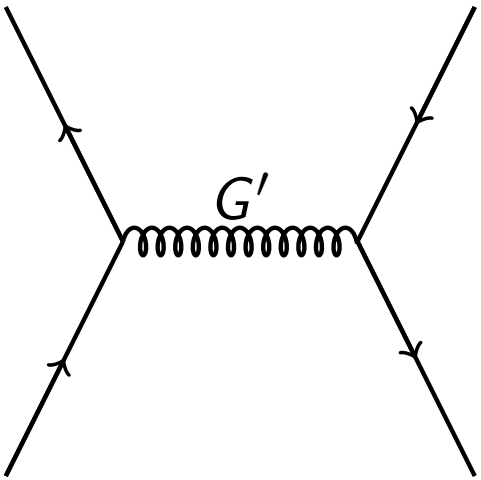
- At Tevatron, charge asymmetry appears as forward-backward asymmetry (θ_t)
- Use top-antitop rapidity difference ($\Delta y = y_t - y_{\bar{t}}$) as proxy for production angle
- Invariant under longitudinal boosts — good for hadron colliders
- $A_{FB} \equiv \dfrac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$

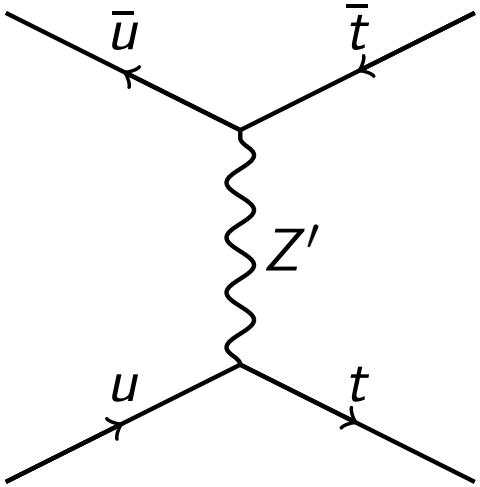
- At leading order, Standard Model predicts zero asymmetry
- Asymmetry at NLO due to:
  - interference between Born and box diagrams (positive)
  - interference between initial state and final state radiation (negative)
- Some disagreement regarding SM predictions:
  - LO/NLO for A_{FB} denominator
  - Size of electroweak corrections
- Inclusive NLO prediction with 26% EWK correction:





$$A_{\mathrm{FB}}^{\mathrm{NLO}} = 6.6\%$$



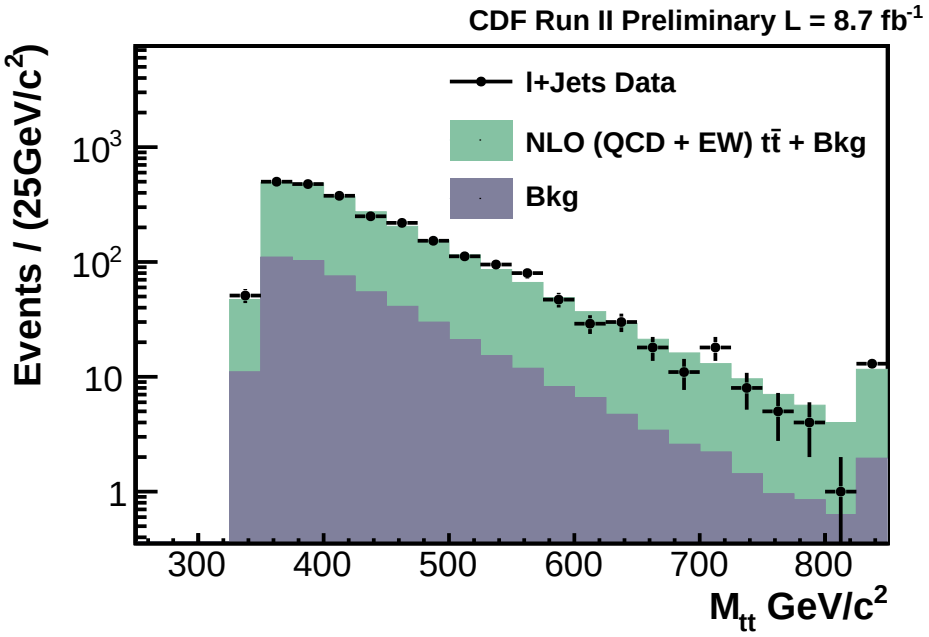


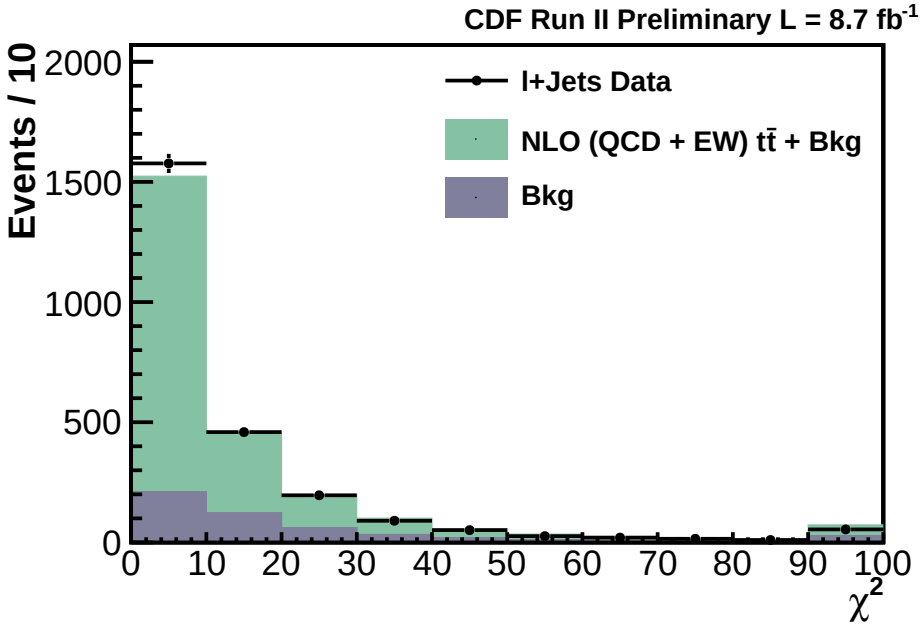
- Two broad classes of new physics add more asymmetry
- s-channel models with heavy color octet:
  - Asymmetry due to axial couplings
  - Expect to see $M_{t\bar{t}}$ resonance
  - Unless G' width very large
- t-channel models with flavor-changing Z':
  - Asymmetry due to flavor-changing into Rutherford peak
  - Expect less deviation from cross section and mass spectrum

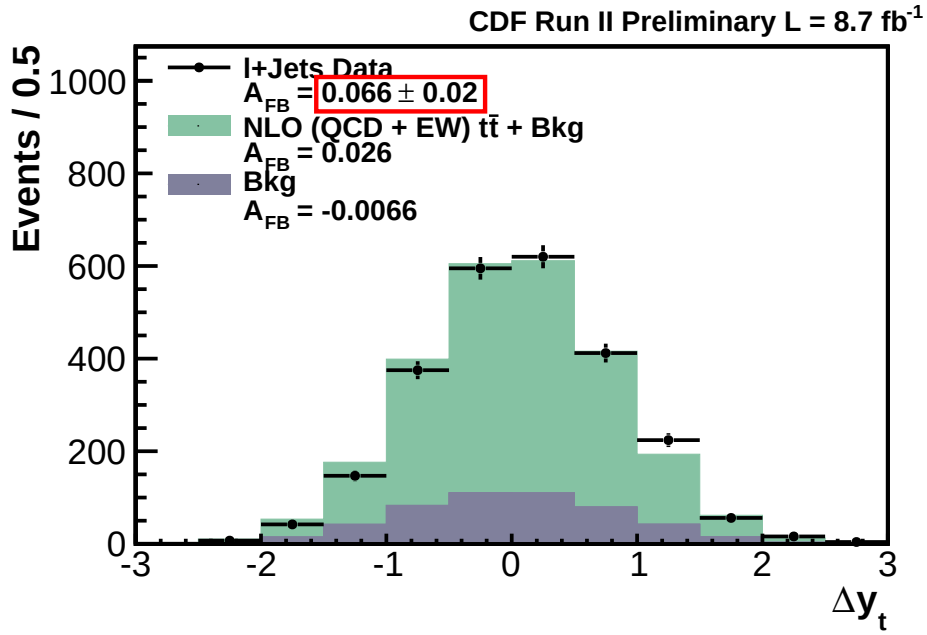
Part II

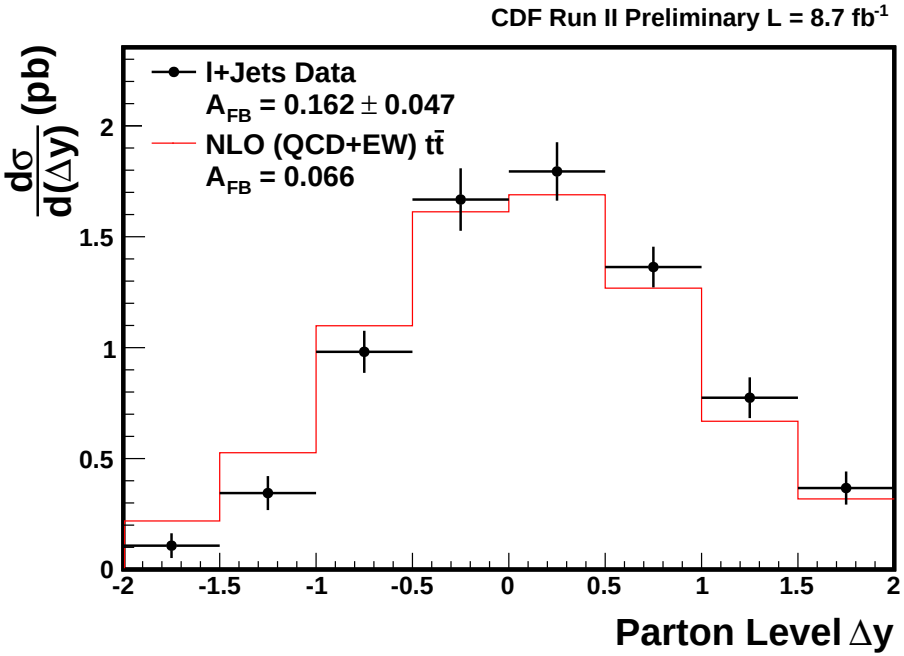
Results

- Lepton+jets, 8.7 fb^{-1}, 2498 events, 505 ± 123 BG
- χ^2 based $t\bar{t}$ reconstruction, constrain M_t, M_W
- SM estimation: Powheg with 26 % EWK correction
- Modeling is good, A_{FB} a little large









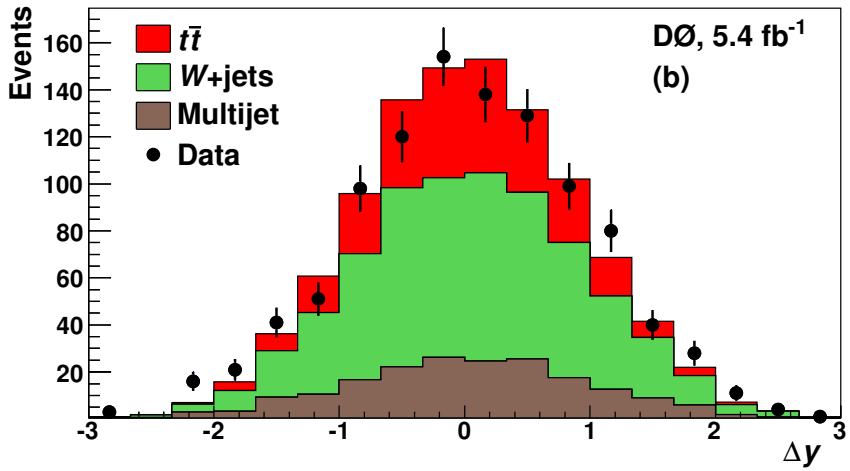
- Unfold to parton level
- SVD regularization
- Predicted A_{FB}: $(6.6 \pm 2.0)\,\%$
- Measured A_{FB}: $(16.2 \pm 4.7)\,\%$
- `http://www-cdf.fnal.gov/physics/new/top/2012/LepJet_AFB_Winter2012/`

- Statistical uncertainties dominate systematic uncertainties

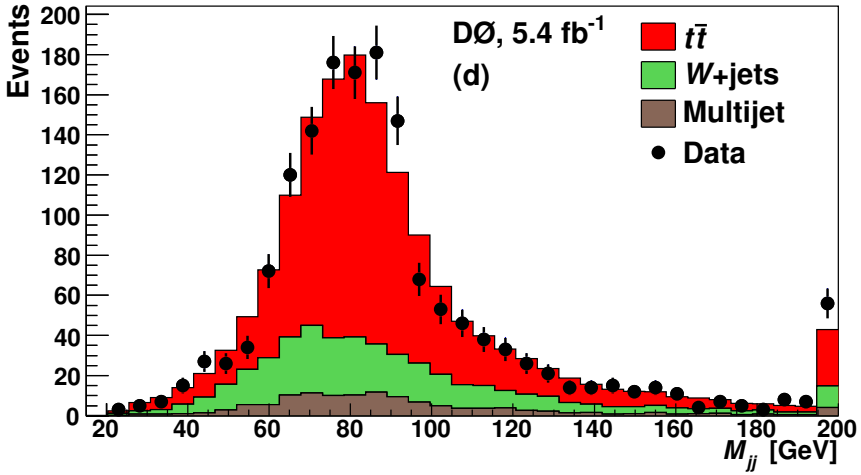
CDF Run II Preliminary L = 8.7 fb^{-1}

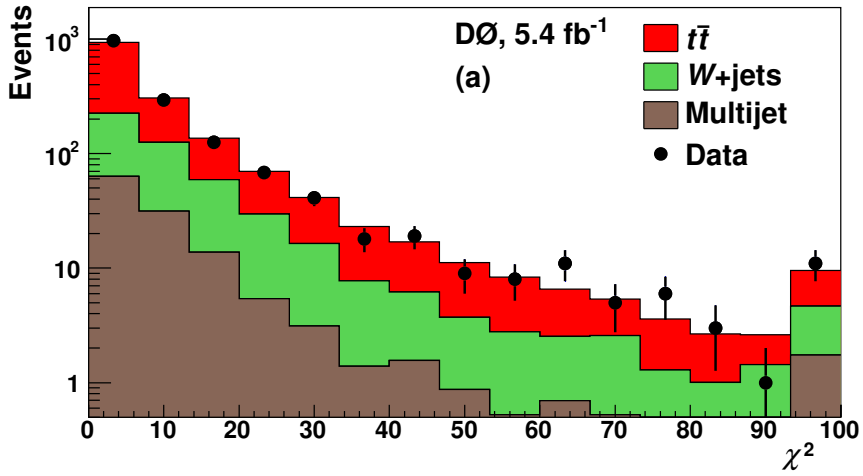
Source	Systematic Uncertainty
Background Shape	0.014
Background Normalization	0.011
Parton Showering	0.010
Jet Energy Scale	0.005
Initial and Final State Radiation	0.005
Color Reconnection	0.001
Parton Distribution Functions	0.001
Correction Procedure	0.003
Total Systematic Uncertainty	0.022
Statistical Uncertainty	0.041
Total Uncertainty	0.047

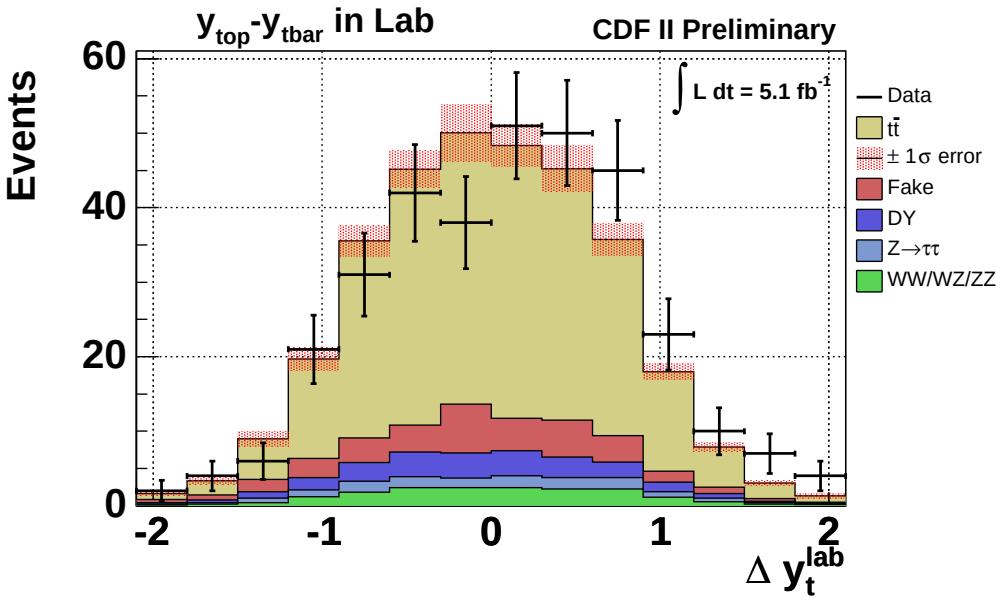
- doi:10.1103/PhysRevD.84.112005
- Lepton+jets, 5.4 fb^{-1}, 1581 events, 455 ± 39 BG
- Similar χ^2 reconstruction
- MC@NLO calculation for SM
- Again, modeling is mostly good, A_{FB} larger than SM
- SVD regularized unfold

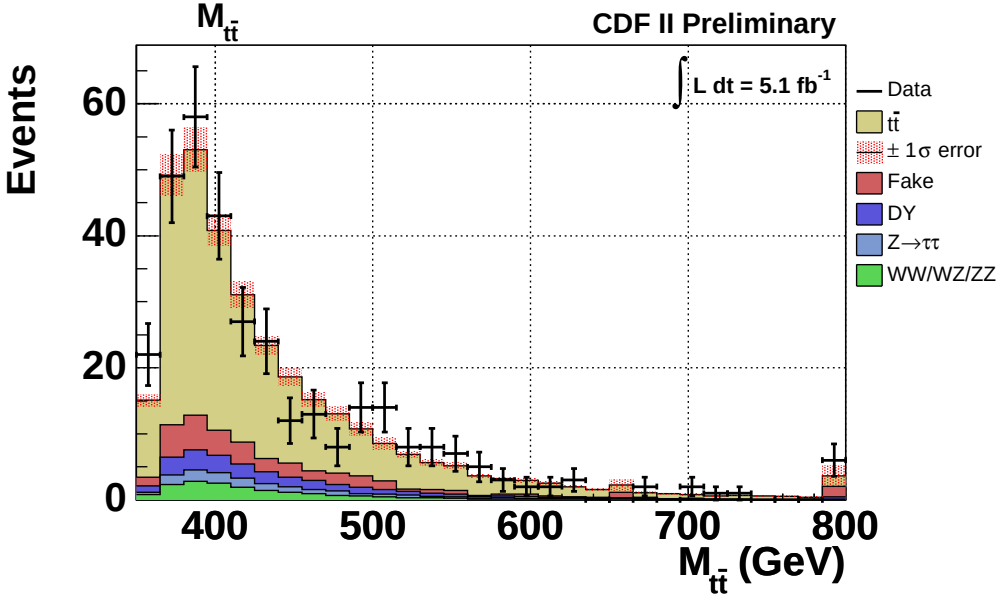


- $A_{\text{FB}}^{\text{observed}} = (9.2 \pm 3.7)\,\%$
- $A_{\text{FB}}^{\text{parton}} = (19.6 \pm 6.5)\,\%$



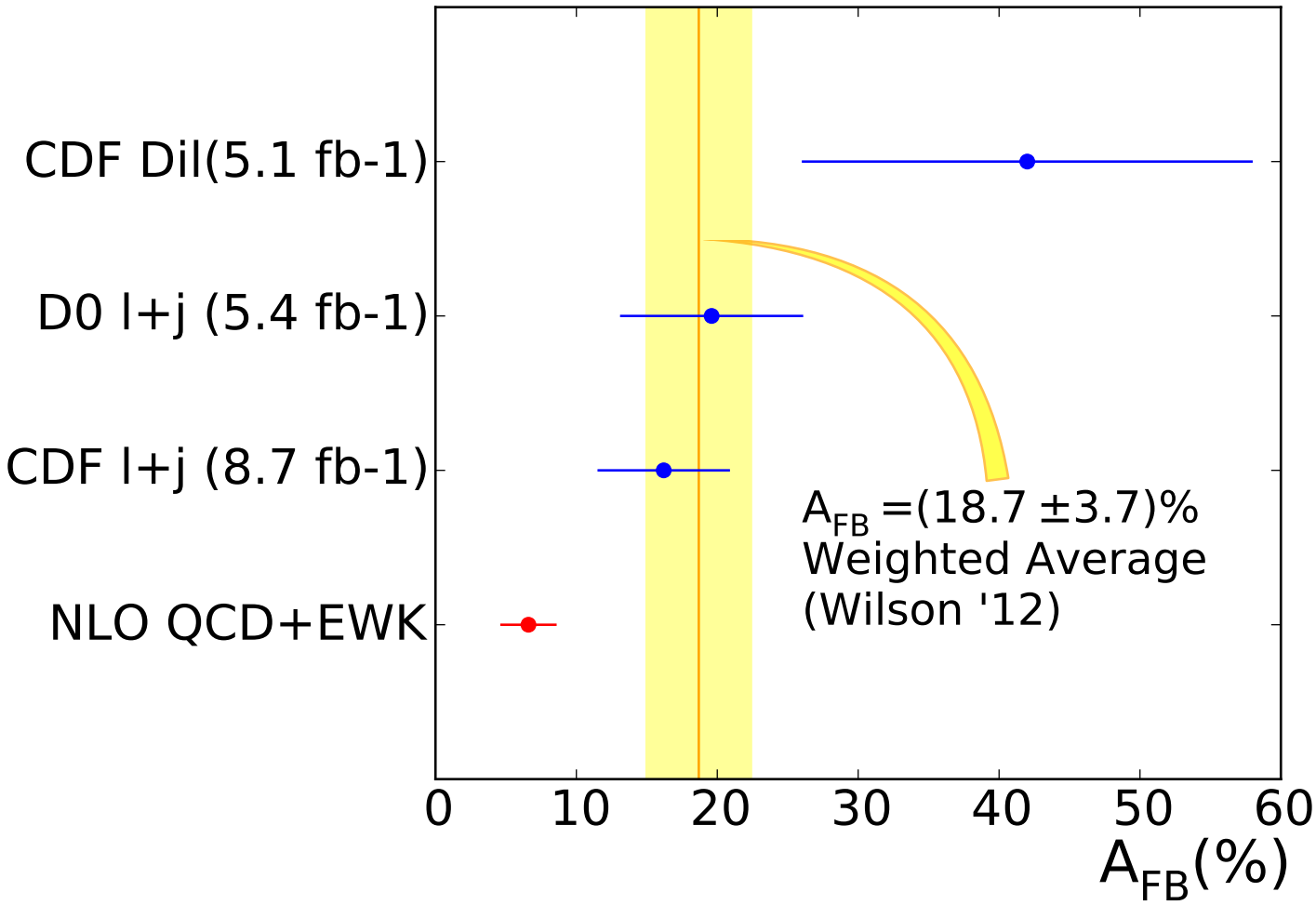






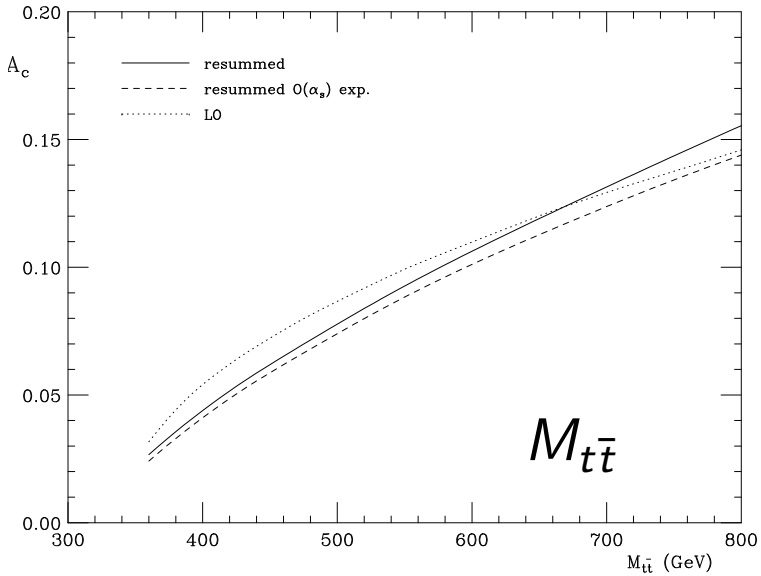
- `http://www-cdf.fnal.gov/physics/new/top/2011/DilAfb/`
- Two OS leptons, met, jets, $5.1\,\text{fb}^{-1}$, 337 events, 87 ± 17 BG
- χ^2 reconstruction with M_W constraint, $p_T(t\bar{t})$, $p_Z(t\bar{t})$ likelihoods
- Parton level unfold via assumption $A_{\text{FB}}(\Delta y) = \alpha \Delta y$
- $A_{\text{FB}}^{\text{observed}} = (13.8 \pm 5.4)\,\%$
- $A_{\text{FB}}^{\text{parton}} = (41.7 \pm 15.7)\,\%$

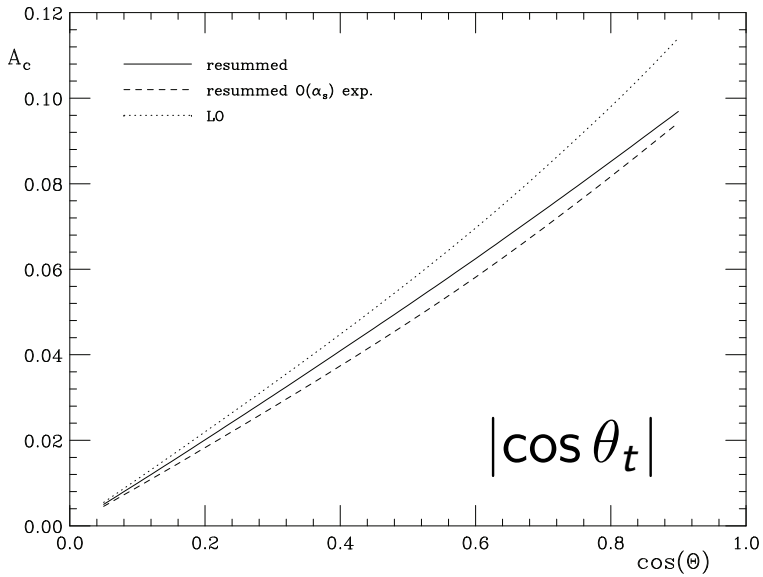
- N.B. NOT a formal combination — private calculation of weighted average only, and correlations are completely neglected
- Experimental results consistent with one another, inconsistent with predicted $(6.6 \pm 2.0)\,\%$



Part III

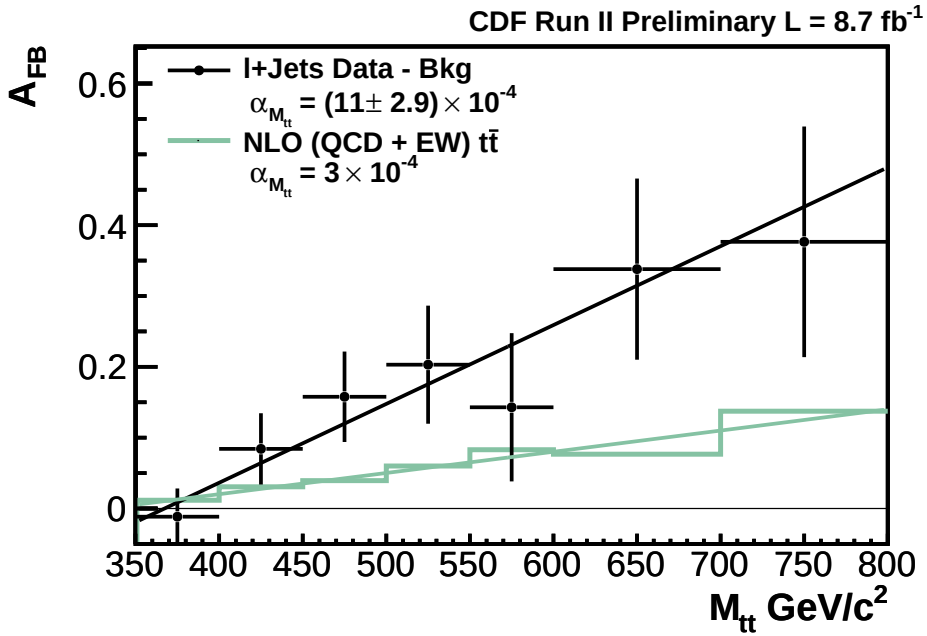
Kinematic dependences

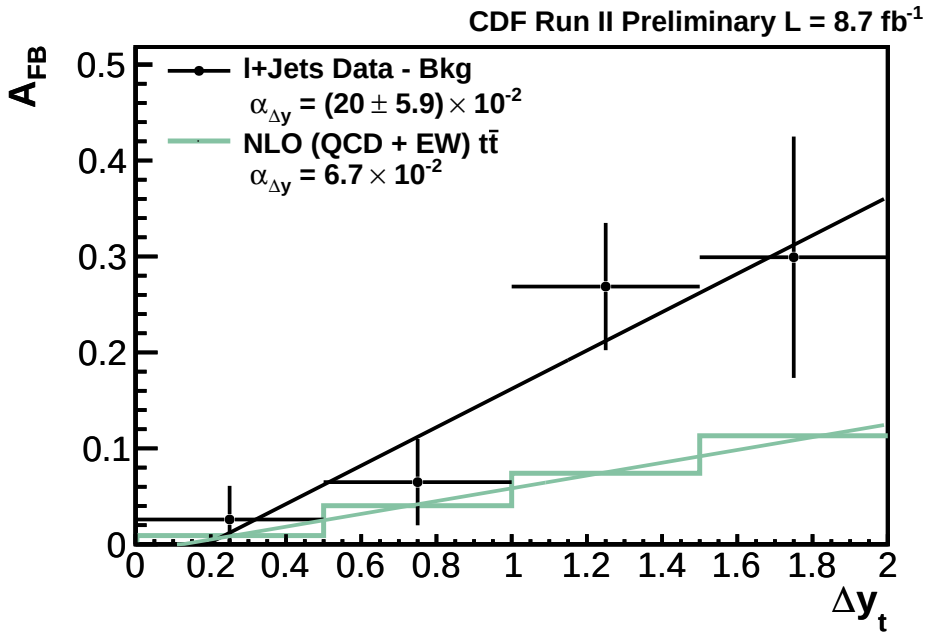


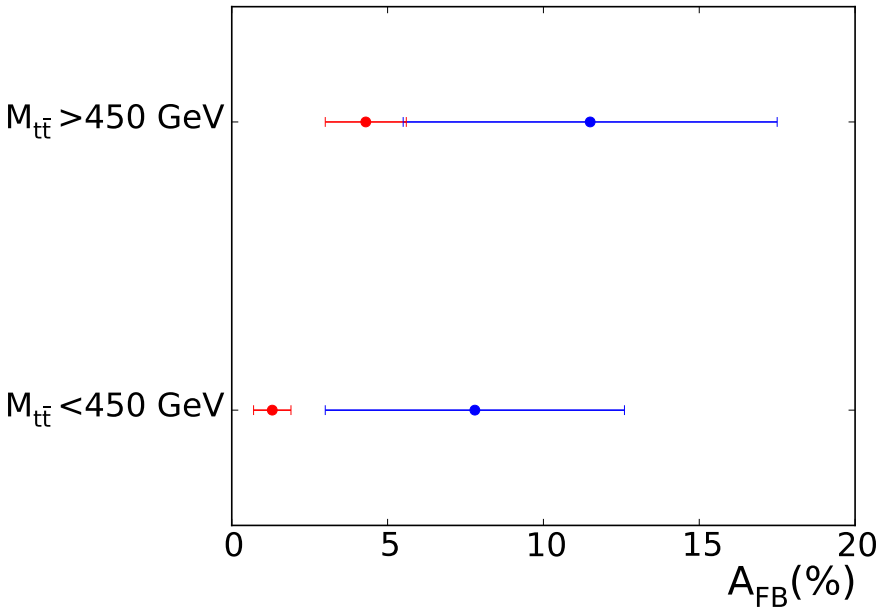


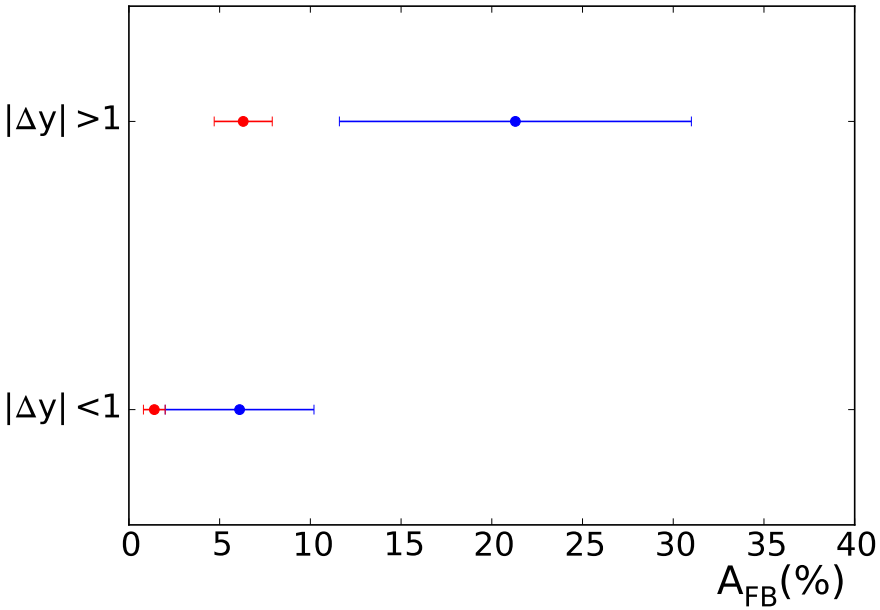
- Asymmetry expected to vary with q^2 ($M_{t\bar{t}}$) and with $|\cos\theta_t|$ ($|\Delta y|$)
- Dependence approximately linear
- Plots from L. Almeida, G. Sterman, and W. Vogelsang, Phys. Rev. D 78, 014008 (2008).

- Fit linear ansatz to measurement
- Fit is pretty good
- Asymmetry increases with $M_{t\bar{t}}$ and with $|\Delta y|$
- Form of increase is as expected
- Magnitude of increase is not
- Run pseudoexperiments to evaluate significance
  - $M_{t\bar{t}}$: $p = 0.00646$
  - $|\Delta y|$: $p = 0.00892$



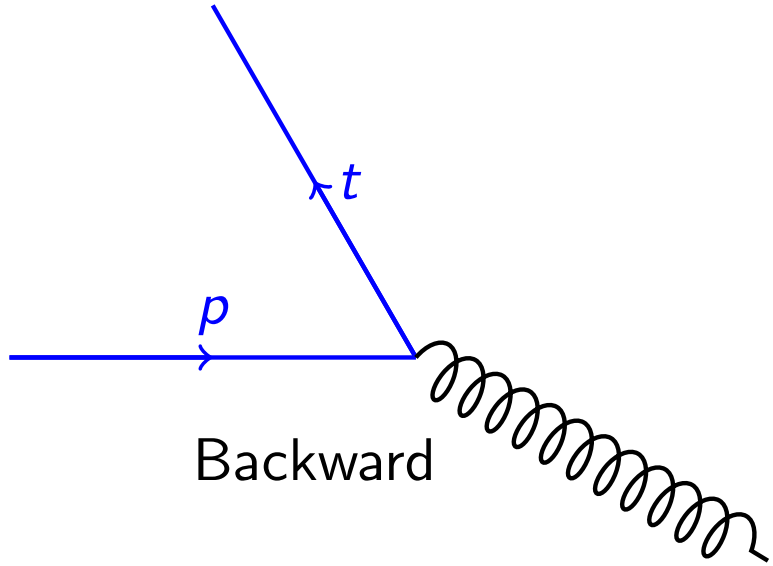


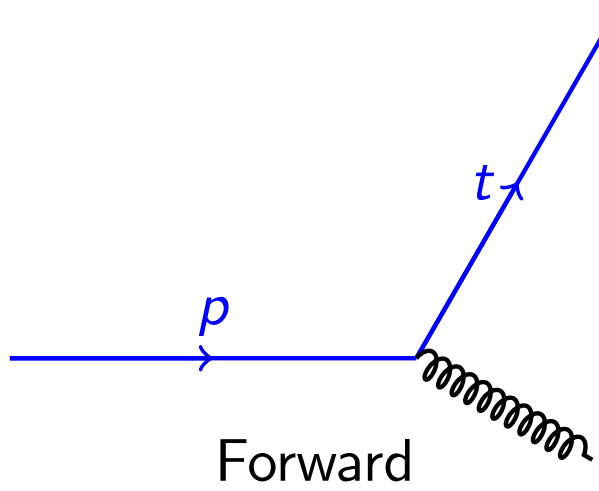




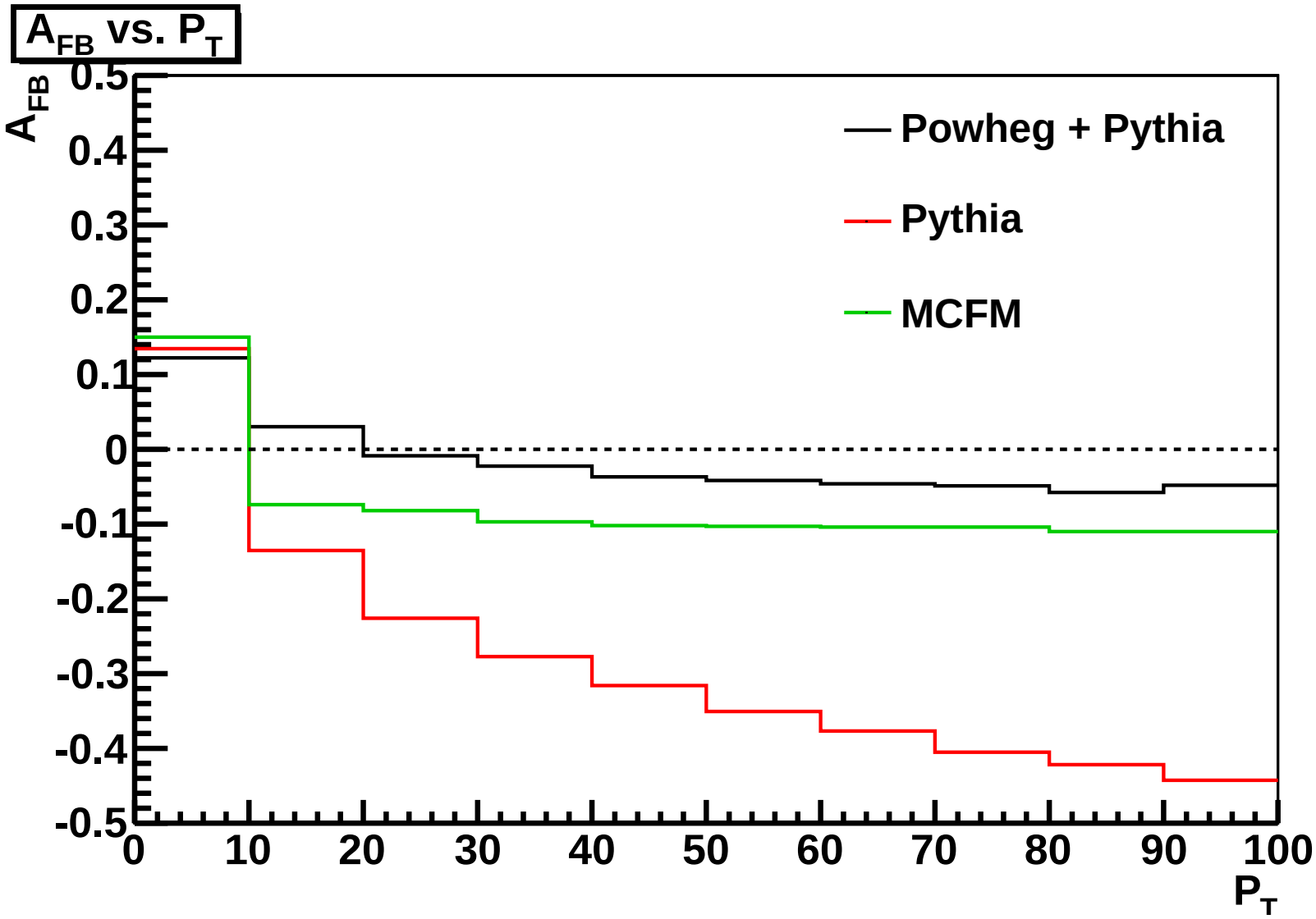
- DZero also studies kinematic dependencies
- Two bins
- No evidence for mass dependence in this DZero data
- Some evidence for a rapidity dependent A_{FB}
- Perhaps a clearer picture with update to full DZero data set

- Dependence of A_{FB} on transverse momentum of $t\bar{t}$ system is very important
- Sensitive to detailed QCD effects
- (Very) rough explanation: In events where top is backwards, color flow from proton to top bends sharply, leading to a "color bremsstrahlung"
- That is, backward events tend to have higher $t\bar{t}$ p_T
- Leads to positive A_{FB} at low p_T, negative at high p_T, even at LO
- Also NLO ISR/FSR interference contributes p_T dependent A_{FB}



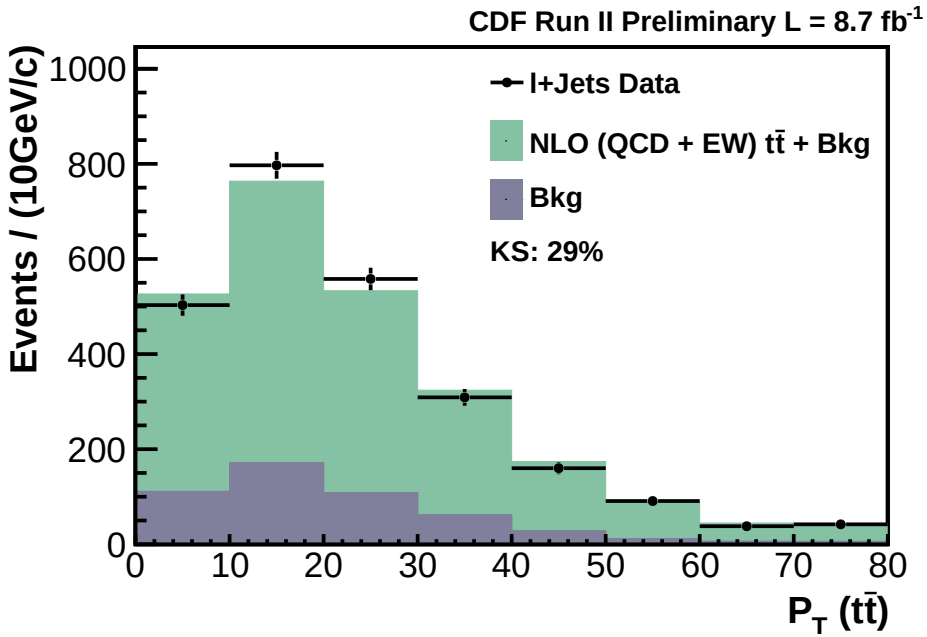


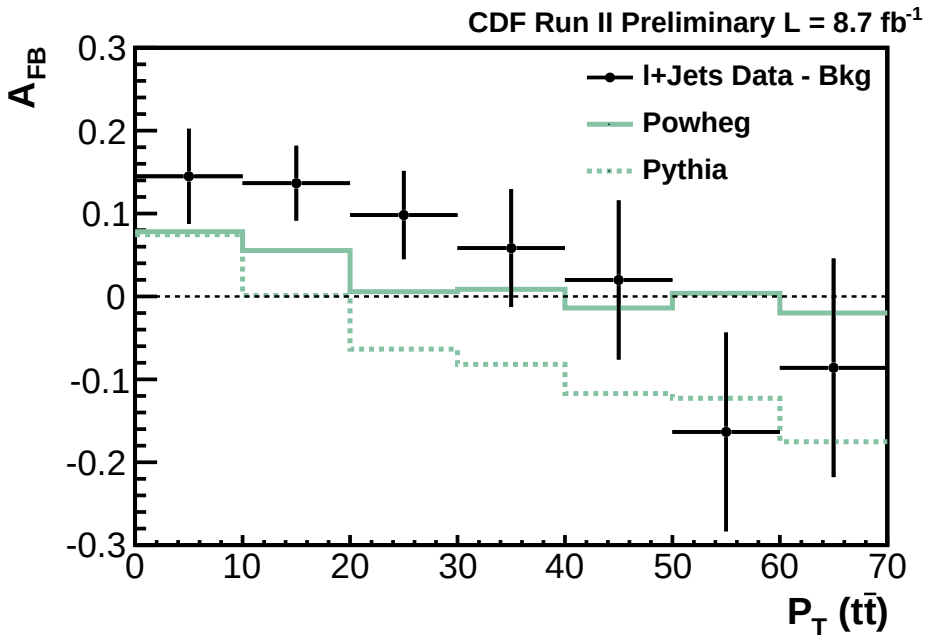
(NOT Feynman diagrams!)



- POWHEG, MCFM, PYTHIA truth
- All same general shape: positive at low p_T, negative at high p_T

- First, is the $t\bar{t}$ p_T spectrum well modeled?
- Important point raised by DZero — if p_T badly modeled, no reason to expect predicted A_{FB} to match data
- Not an easy quantity to do well with
- Anthing "left over" in event goes into p_T: underlying event, pileup, instrumental noise, etc.
- Modeling looks fine in CDF data



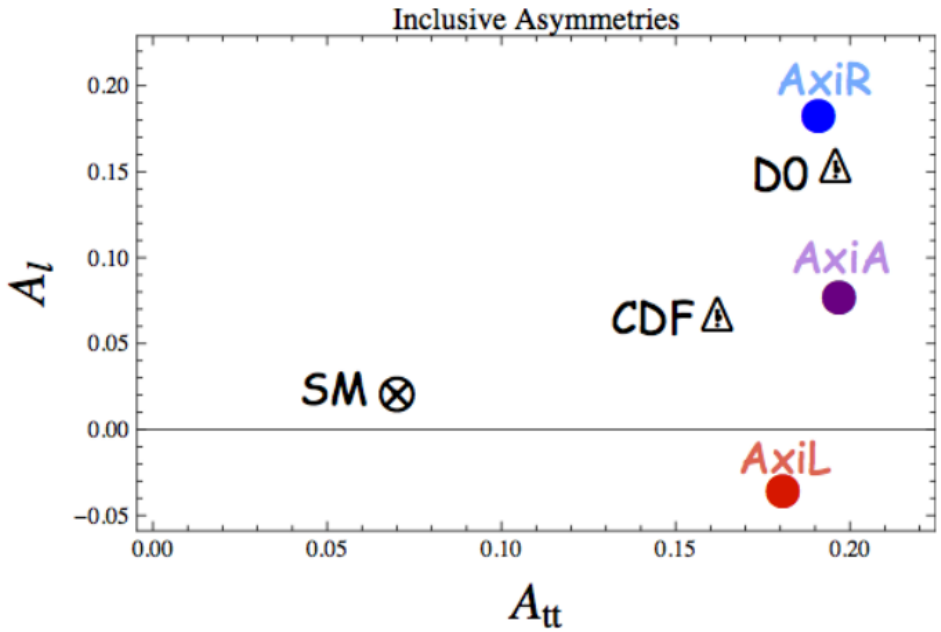


- Behavior of the models largely survives detector and reconstruction effects
- Our data (background subtracted) shows a similar dependence on p_T
- Larger overall asymmetry
- Shape compatible with SM predictions from POWHEG and from PYTHIA, total asymmetry not compatible

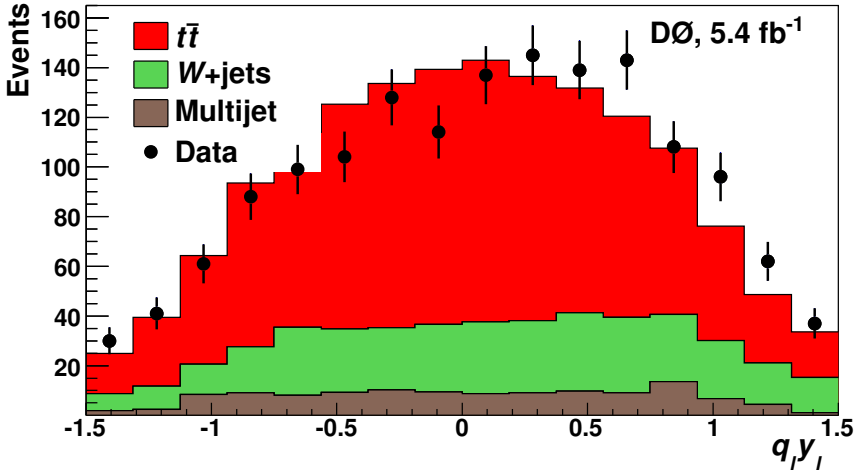
Part IV

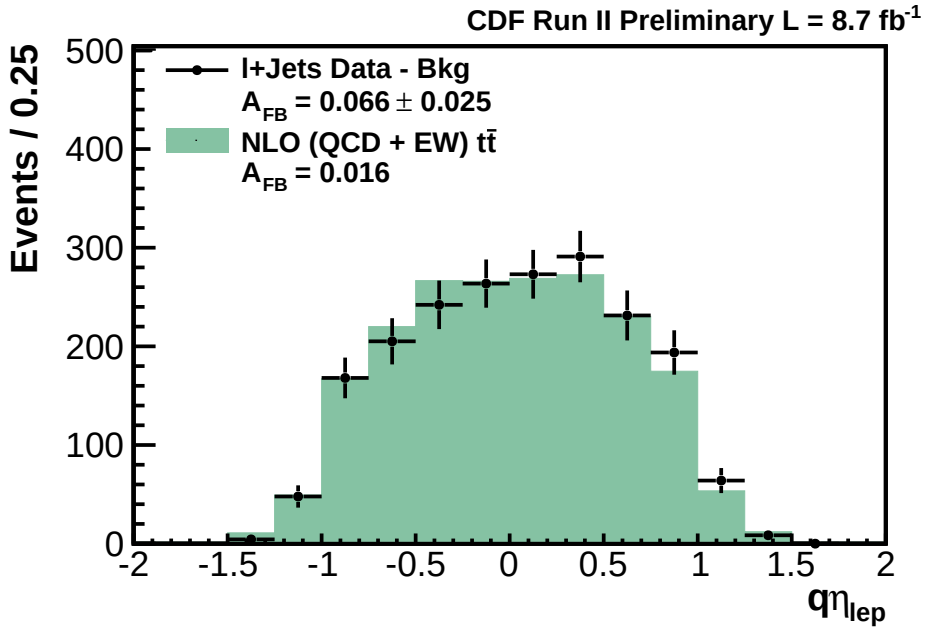
Lepton asymmetries

- Lepton direction $\sim$ top direction
- Get lepton information without $t\bar{t}$ reconstruction
- Independent check of asymmetries
- If tops are produced polarized, can see this in lepton A_{FB}
- Falkowski '12



Charge-weighted lepton psuedorapidity ($Q \cdot \eta_\ell$)

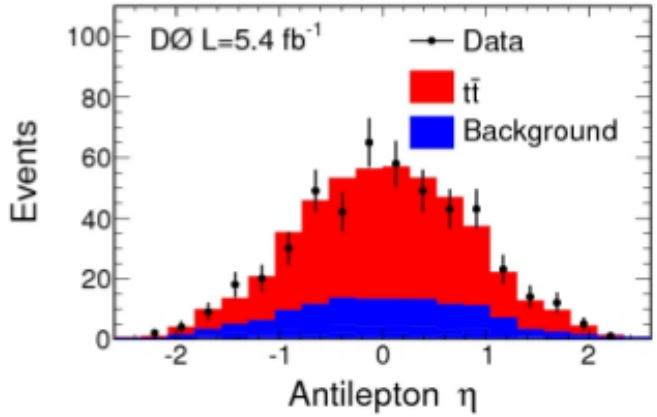


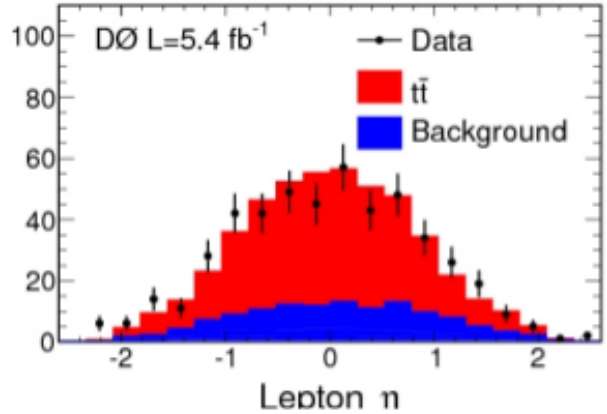


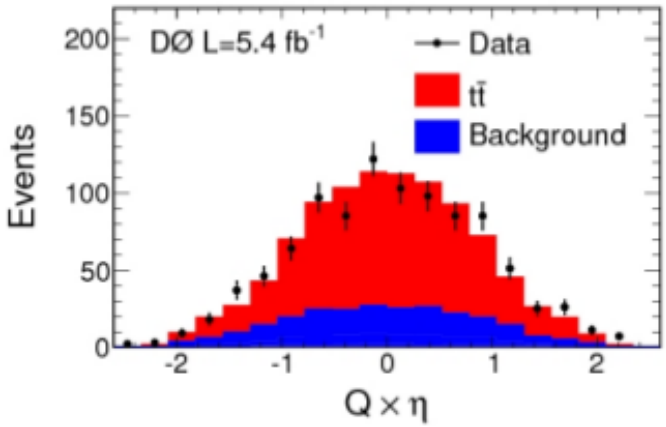
- $A_{\mathrm{FB}}^{\ell,\mathrm{obs}} = (14.2 \pm 3.8)\,\%$
- $A_{\mathrm{FB}}^{\ell,\mathrm{pred}} = (0.8 \pm 0.6)\,\%$
- Also unfold to parton level
- $A_{\mathrm{FB}}^{\ell,\mathrm{parton}} = (15.2 \pm 4.0)\,\%$
- $A_{\mathrm{FB}}^{\ell,\mathrm{pred}} = (2.1 \pm 0.1)\,\%$

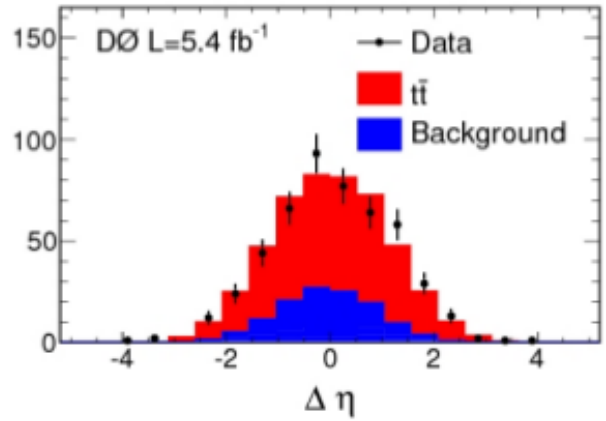
- Inclusive:
  - $A_{\mathrm{FB}}^{\ell,\mathrm{obs}} = (6.6 \pm 2.5)\,\%$
  - $A_{\mathrm{FB}}^{\ell,\mathrm{pred}} = (1.6 \pm 0.5)\,\%$
- $M_{t\bar{t}} > 450\,\mathrm{GeV}/c^2$:
  - $A_{\mathrm{FB}}^{\ell,\mathrm{obs}} = (11.6 \pm 4.2)\,\%$
  - $A_{\mathrm{FB}}^{\ell,\mathrm{pred}} = (3.2 \pm 1.0)\,\%$

- arXiv:1207.0364
- $5.4\,\mathrm{fb}^{-1}$, two OS leptons, Z veto, 2 jets, MET, H_T
- 649 events, 244 ± 18 BG
- Only addresses the leptons — no $t\bar{t}$ reconstruction









	Raw	Unfolded	Predicted
A^{ℓ}	$2.9 \pm 6.1 \pm 0.9$	$2.5 \pm 7.1 \pm 1.4$	4.7 ± 0.1
$A_{\mathrm{FB}}^{\ell^+}$	$4.5 \pm 6.1 \pm 1.1$	$4.1 \pm 6.8 \pm 1.1$	4.4 ± 0.2
$A_{\mathrm{FB}}^{\ell^-}$	$-1.2 \pm 6.1 \pm 1.3$	$-8.4 \pm 7.4 \pm 2.4$	-5.0 ± 0.2
A_{FB}^{ℓ}	$3.1 \pm 4.3 \pm 0.8$	$5.8 \pm 5.1 \pm 1.3$	4.7 ± 0.1
$A^{\ell\ell}$	$3.3 \pm 6.0 \pm 1.1$	$5.3 \pm 7.9 \pm 2.9$	6.2 ± 0.2
A_{CP}^{ℓ}	$1.8 \pm 4.3 \pm 1.0$	$-1.8 \pm 5.1 \pm 1.6$	-0.3 ± 0.1

- Many different measurements are possible in dileptons
- All consistent with SM prediction, with large error bars
- Combine single-lepton A_{FB} ($(5.8 \pm 5.3)\,\%$) with same from lepton+jets
- BLUE gives $(11.8 \pm 3.2)\,\%$ — two measurements 68 % consistent with one another

- $A_{\mathrm{FB}}^{t\bar{t}}$ remains an interesting and reproducible effect
- Not (yet?) well understood in the Standard Model
- At CDF and DZero, we have been and continue to be working hard to fully characterize the asymmetry
- Investigated dependence on mass, rapidity, and transverse momentum
- Lepton-only asymmetries give both a cross check and a polarization probe

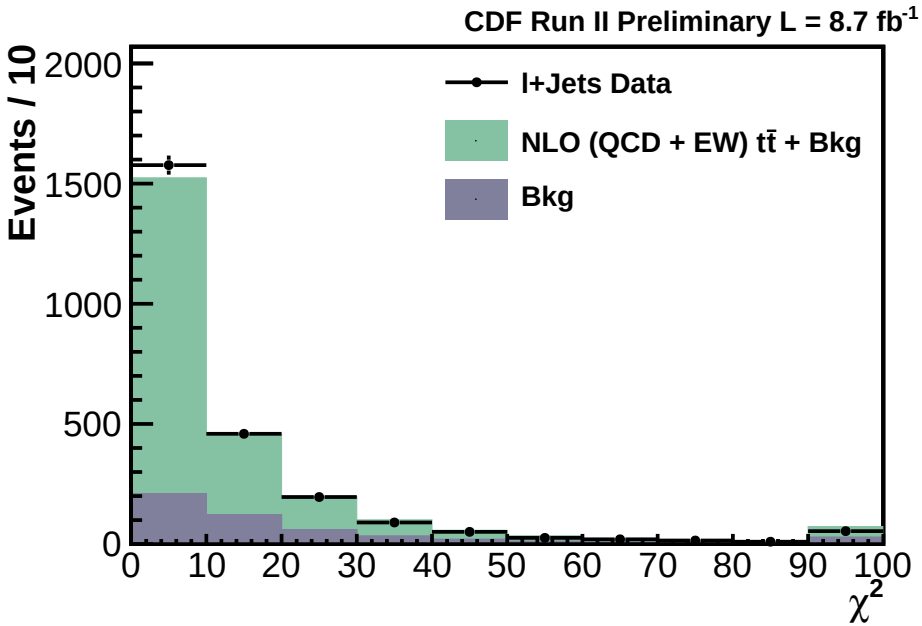
Part V

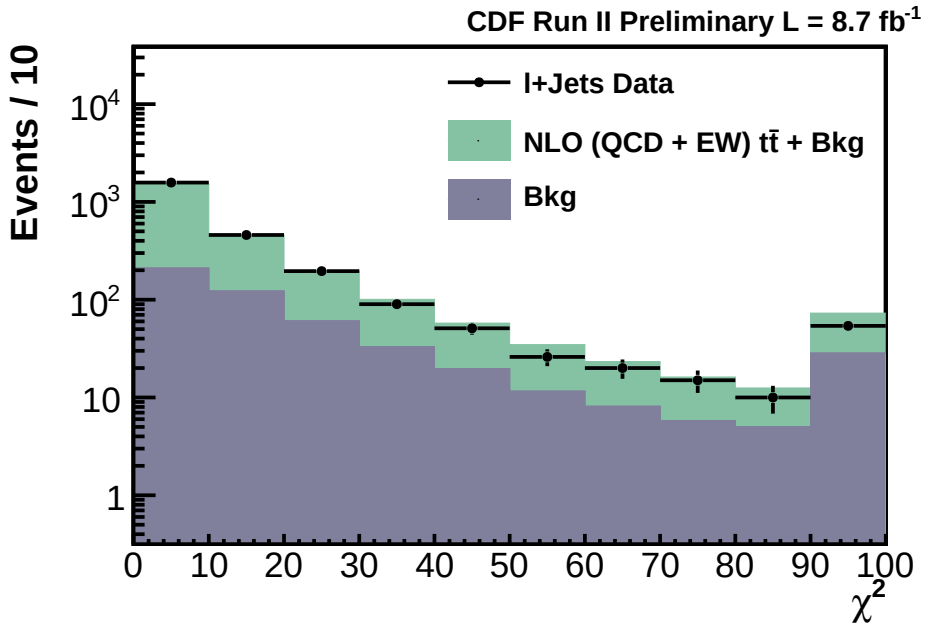
Appendix

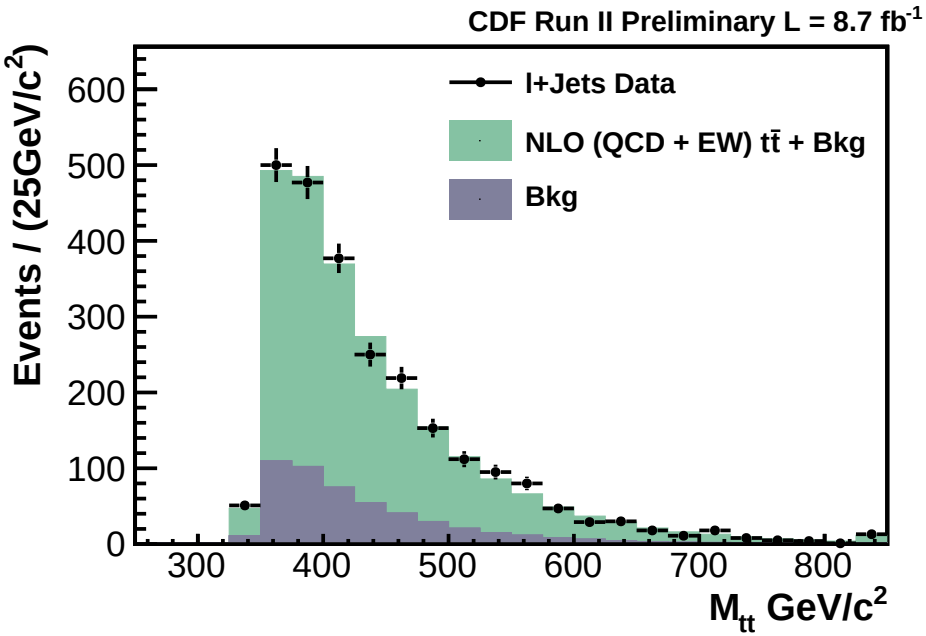
- Look for lepton + jets: $t\bar{t} \to WbWb \to \ell\nu bqqb$
- Using the full Tevatron dataset of 8.7 fb^{-1}, select a sample of events with
  - Well-reconstructed lepton
  - Missing transverse energy
  - At least 4 jets with $E_T > 20\,\text{GeV}$
  - At least one b-tagged jet
  - Total energy $(H_T) > 220\,\text{GeV}$
- 2498 candidate $t\bar{t}$ events
- 2037 expected $t\bar{t}$ events, 505 expected background events
- Quite pure sample of $t\bar{t}$ (4:1)

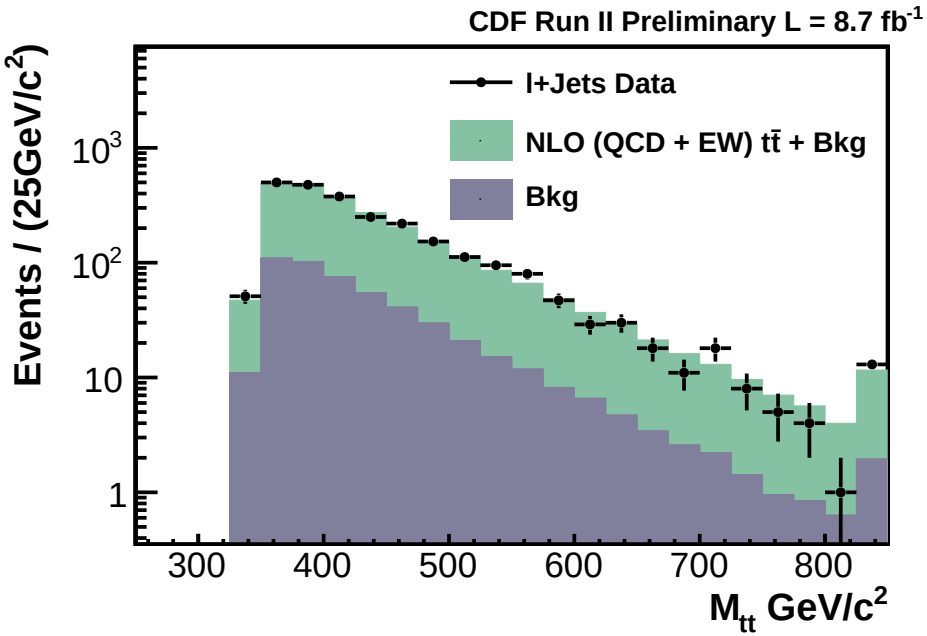
Source	Predicted Event Count, 8.7 fb^{-1}
W + Heavy Flavor	241 ± 78
Non-W (QCD)	98 ± 51
W + Light Flavor	96 ± 29
Single Top	33 ± 2
Diboson	19 ± 3
Z + Jets	18 ± 2
Total Background	505 ± 123
Top Pairs (7.4 pb)	2037 ± 277
Total Prediction	2542 ± 303
Data	2498

- Reconstruct $t\bar{t}$ system using χ^2 based fitter
- W masses constrained to $80.4\,\mathrm{GeV}/c^2 \pm \Gamma_W$ — get neutrino p_Z
- t masses constrained to $172.5\,\mathrm{GeV}/c^2 \pm \Gamma_t$
- Jet energies and unclustered energy float within uncertainties
- Try all permutations of leading 4 jets (b-tagged jets matched to b quarks), use best fit
- Distribution of best χ^2 well-modeled over 2 orders of magnitude, even for very large χ^2

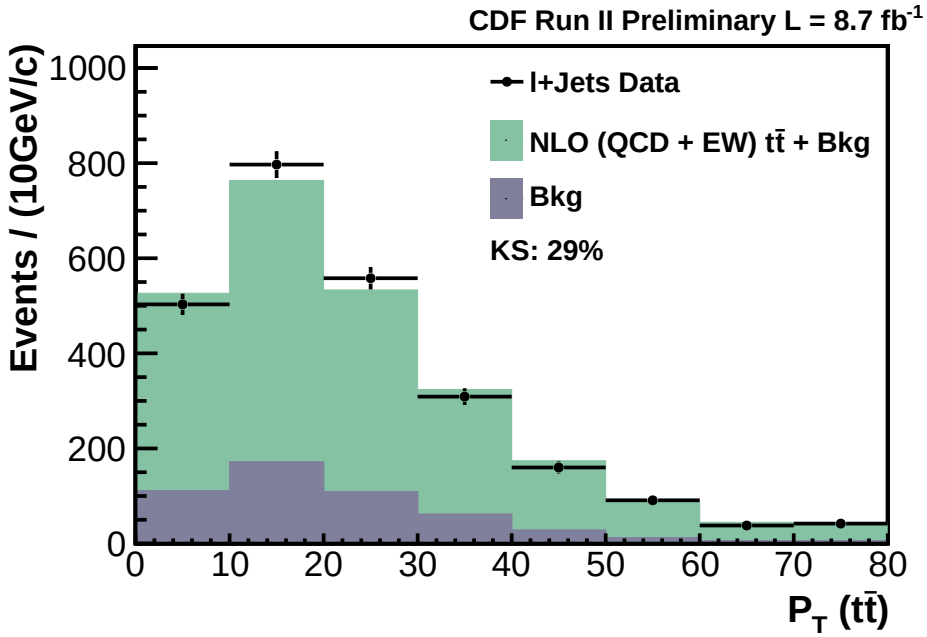


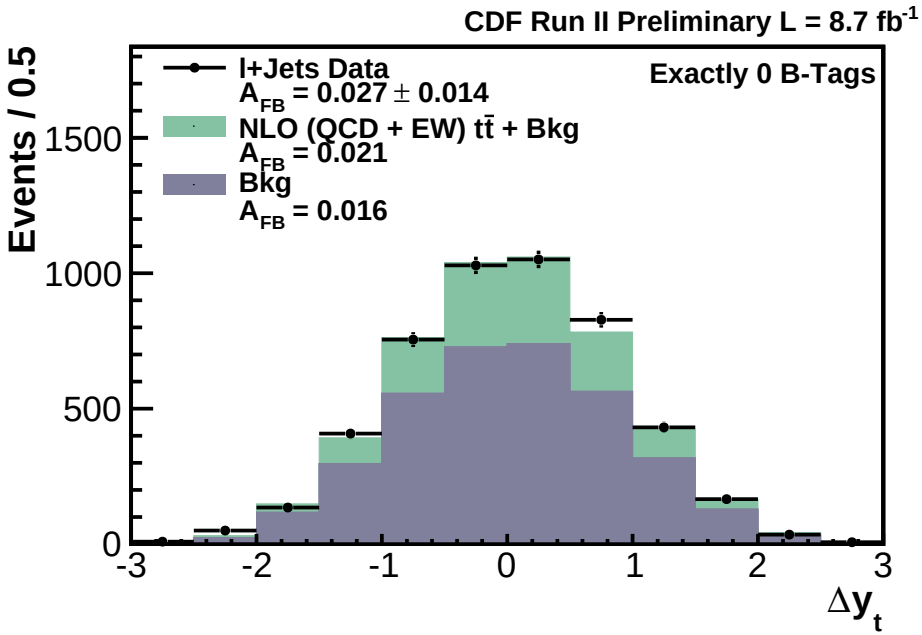




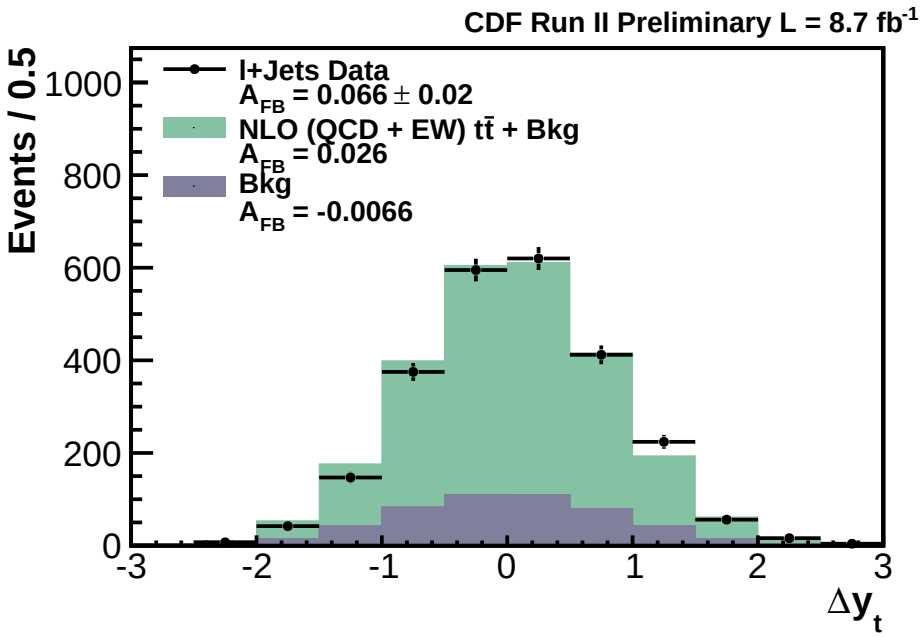


- $t\bar{t}$ mass spectrum (proxy variable for q^2) also well modeled
- Transverse momentum of $t\bar{t}$ system is a sensitive check of our reconstruction and modeling
- Anything left over in event goes into p_T — modeling looks fine

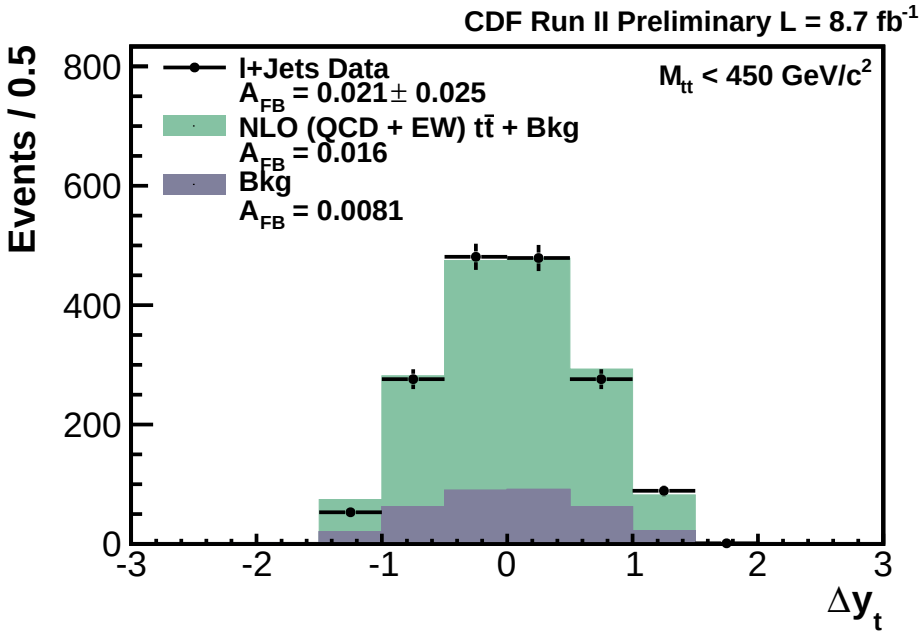


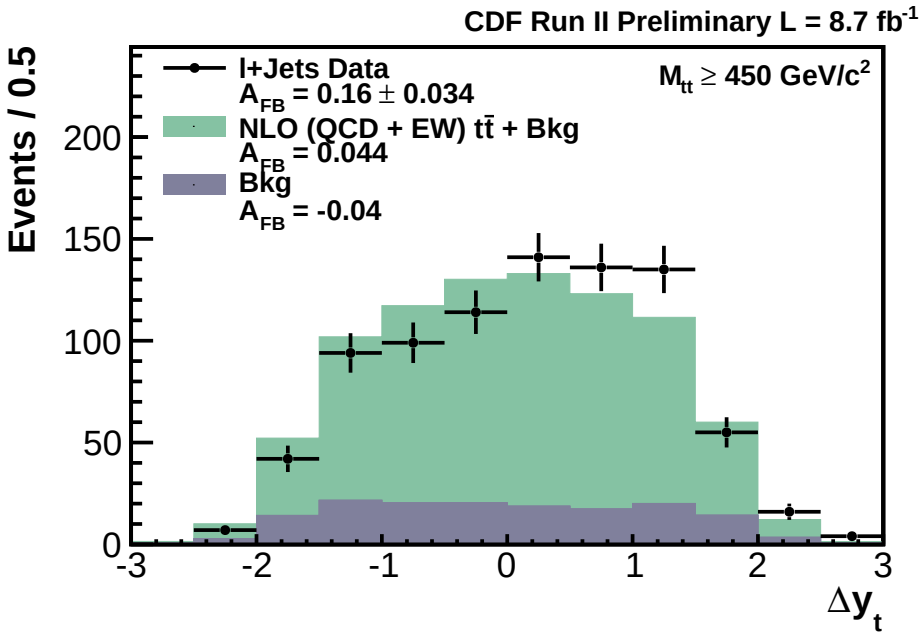


- Side-band: exactly ZERO b-tagged jets
- Depleted in $t\bar{t}$
- Plenty of data
- Check variable of interest — Δy
- Expected asymmetry small (2.1%)
- Observed asymmetry small (2.7%)
- Good modeling builds confidence for signal region



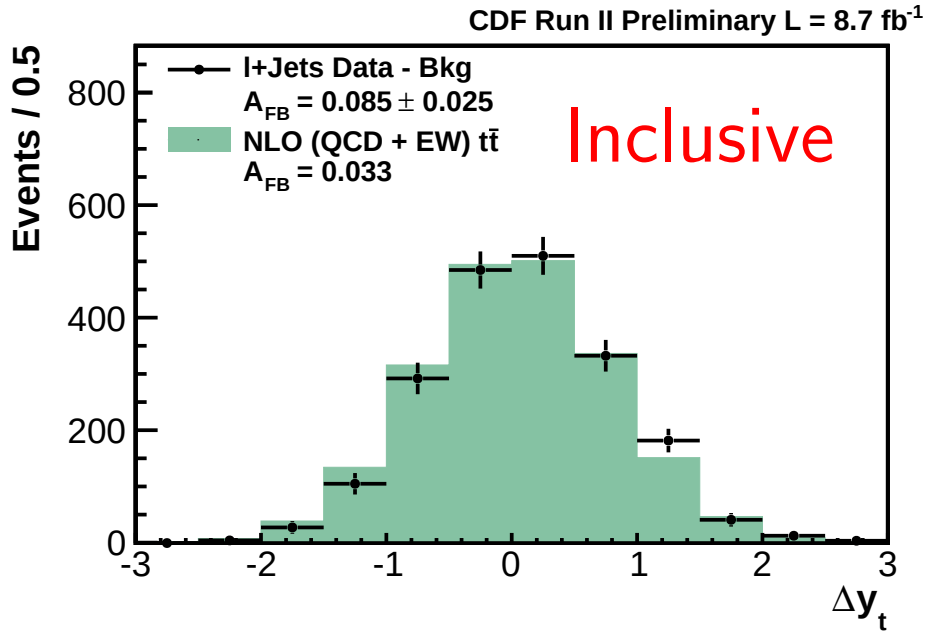
- Back to signal region
- Expected asymmetry due to NLO $t\bar{t}$ with EWK corrections plus backgrounds: 2.6 %
- But we observe an asymmetry of (6.6 ± 2.0) %
- This is enough to investigate further

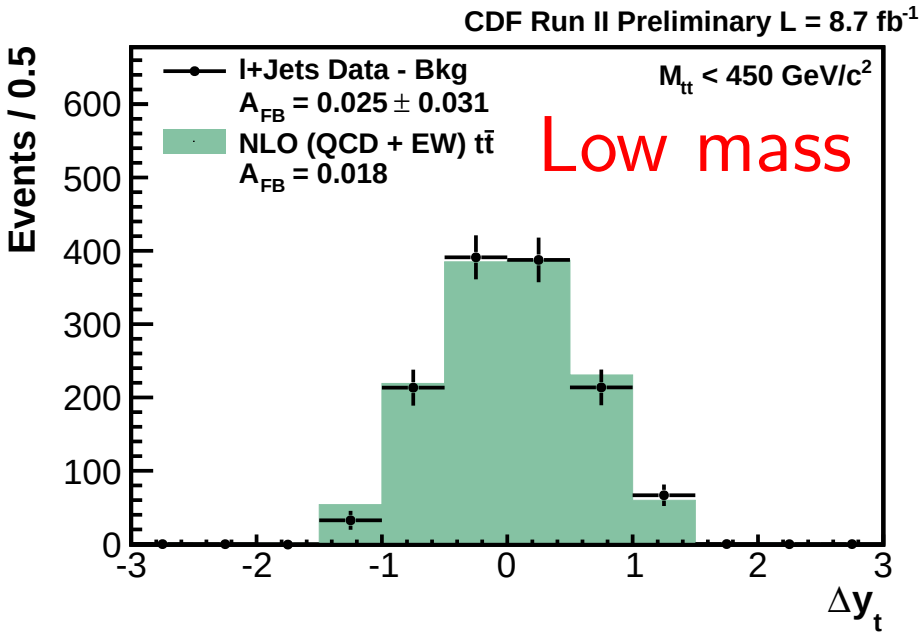


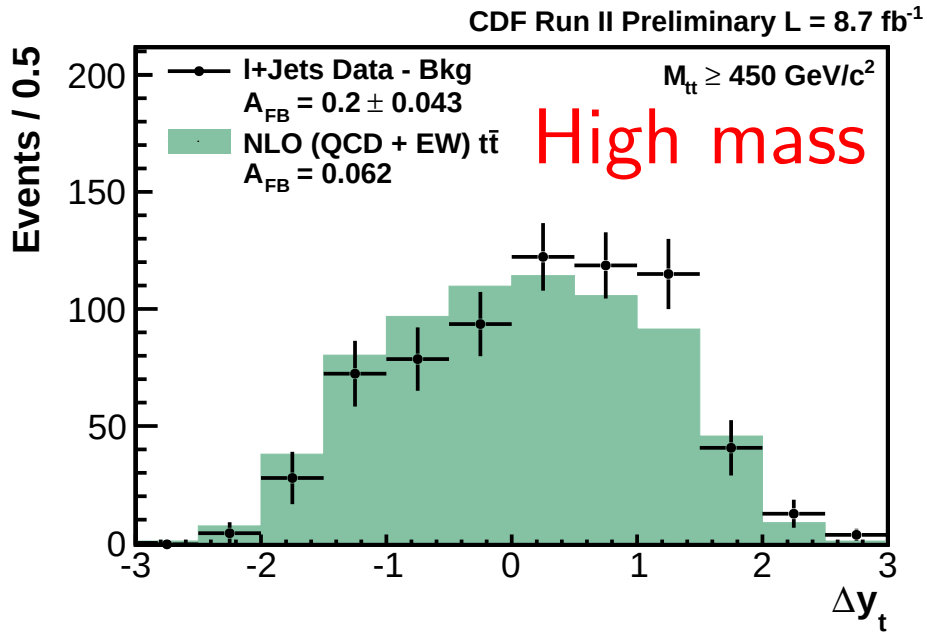


- Since SM asymmetry depends on $M_{t\bar{t}}$, split sample at $450\,\mathrm{GeV}/c^2$
- $M_{t\bar{t}} < 450\,\mathrm{GeV}/c^2$ has asymmetry consistent with zero and with SM
- $M_{t\bar{t}} > 450\,\mathrm{GeV}/c^2$: $A_{\mathrm{FB}} = (16.0 \pm 3.4)\,\%$ versus expected $4.4\,\%$

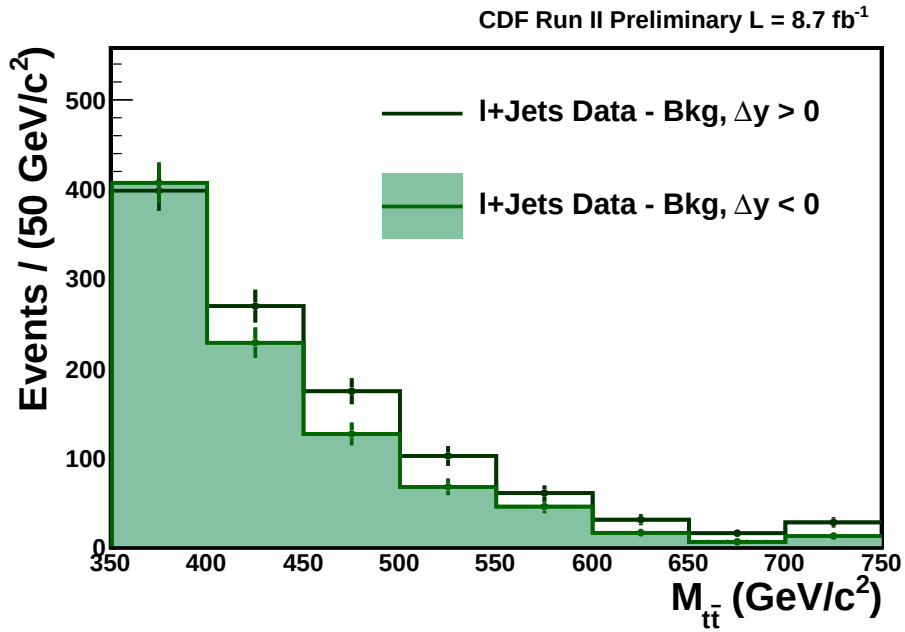
- To focus in on $t\bar{t}$, subtract the background model from data and compare to $t\bar{t}$ MC
- Still see similar effects in Δy, inclusively as well as above and below 450 GeV/c^2

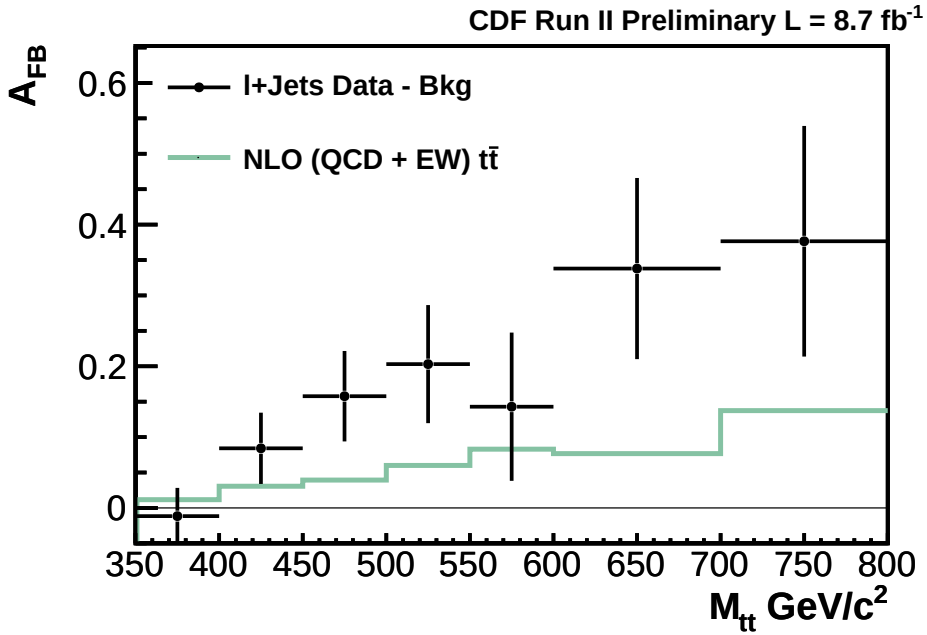




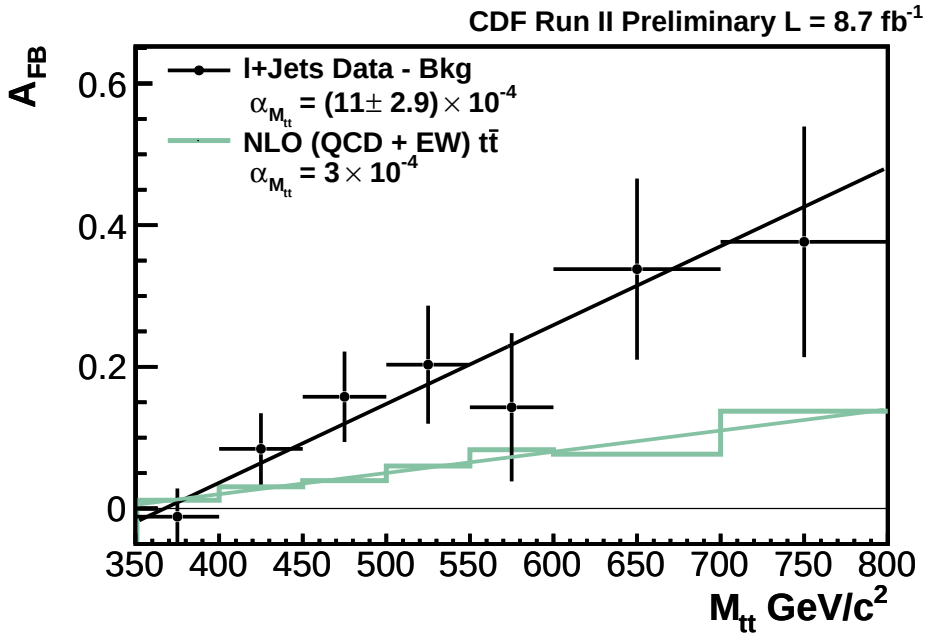


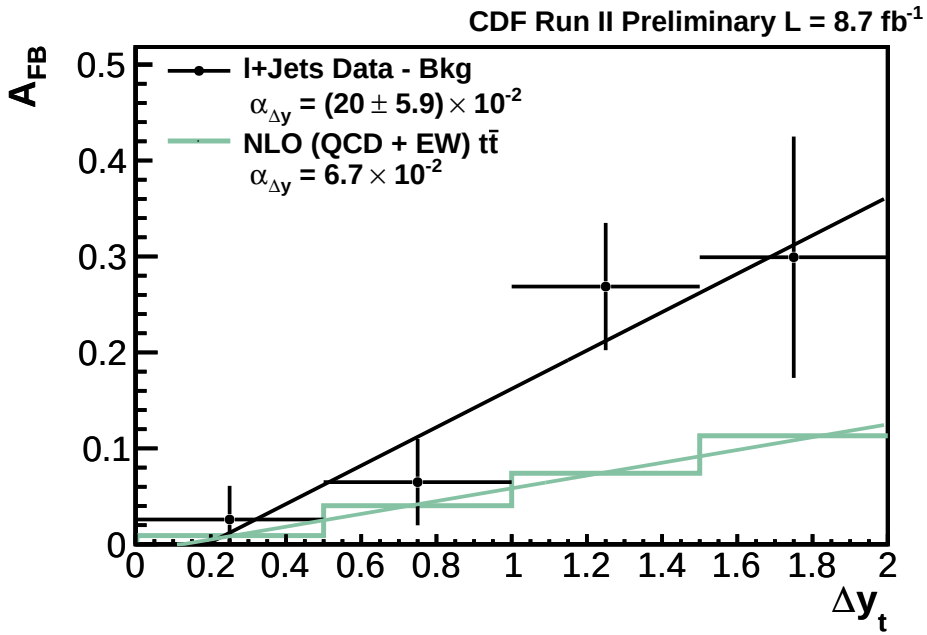
- With the full Tevatron dataset, investigate mass dependence more thoroughly
- Enough data for more than 2 bins
- Mass spectrum for forward ($\Delta y > 0$) and backward ($\Delta y < 0$) events noticeably different in the data
- A_{FB} rises evenly with $M_{t\bar{t}}$
- Magnitude of A_{FB} increase not predicted by SM.



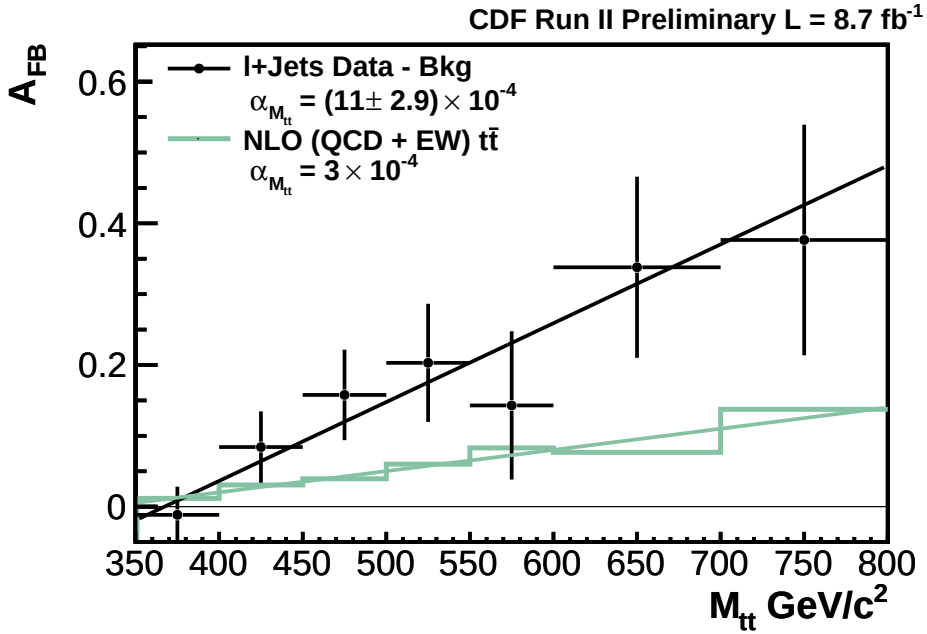


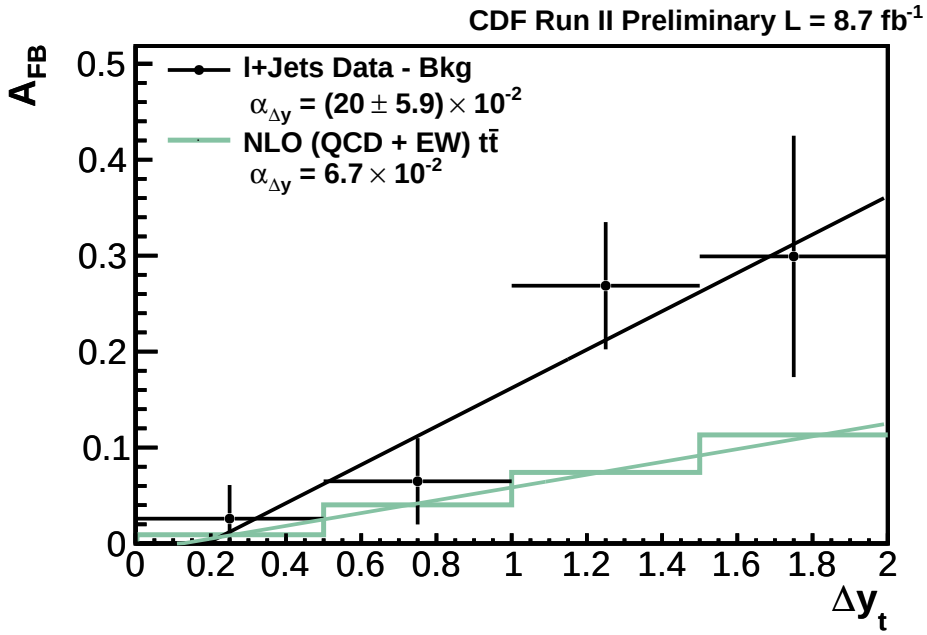
- SM predicts $\sim$ linear dependence on q^2
- Fit linear ansatz to data and to SM prediction
- SM also predicts $\sim$ linear dependence on $\cos\theta_t$
- Fit linear ansatz to A_{FB} vs. Δy
- Both SM prediction and data well described by linear dependence on $M_{t\bar{t}}$ and Δy
- N.B. slope is not a theory parameter





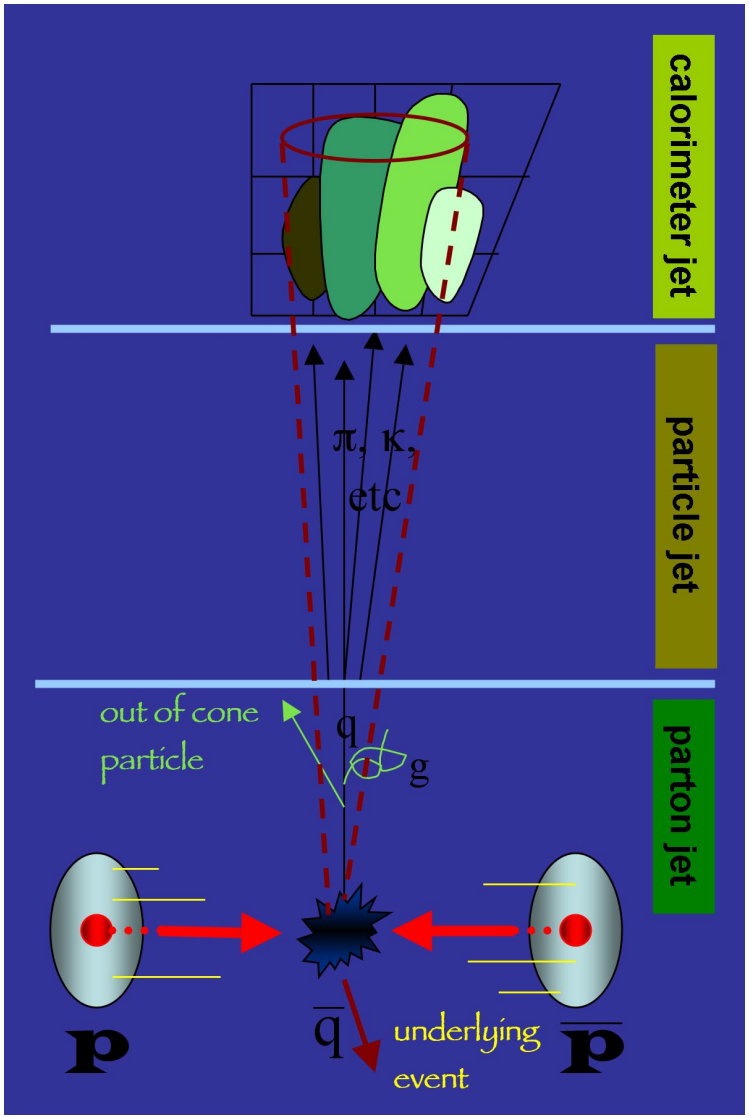
- Perform pseudoexperiments with POWHEG
- Produce these distributions for each pseudoexperiment
- Fit linear ansatz to each pseudoexperiment
- Count number of pseudoexperiments with slope this large or larger
- *p*-values:
  - $M_{t\bar{t}}$ dependence: 0.00646
  - Δy dependence: 0.00892
- To compare data directly to theory or other experiments, data must be corrected to parton level





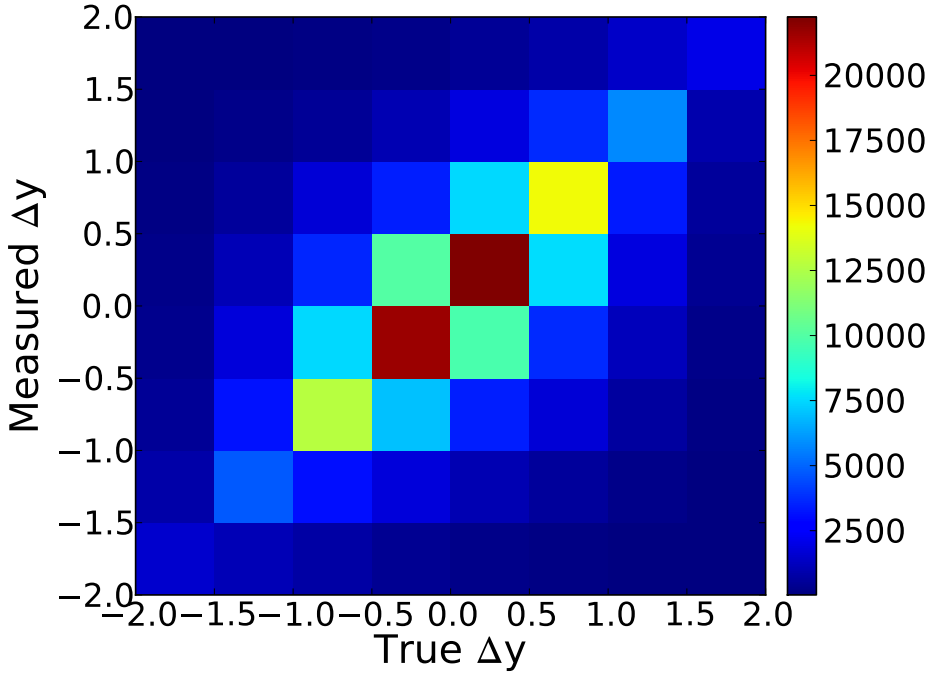
Part VI

Parton corrected



- To estimate parton-level distributions from data, we must account for:
  1. Finite detector resolution
  2. Smearing due to incorrect reconstruction
  3. Effect of selection cuts
  4. Geometric acceptance
  5. Trigger rate
  6. Finite statistics
- Two steps – first unsmear to correct for 1, 2, and 6, then correct acceptance for 3, 4 and 5
- Acceptance correction is simple bin-by-bin ratio of MC truth before and after selection

- Estimate detector response matrix S from Monte Carlo
- Linear equation for corrected data $\vec{x}$ from data $\vec{b}$: $S\vec{x} = \vec{b}$
- Inverse problem is ill-conditioned
- Can only be solved in least squares sense (min $\left|S\vec{x} - \vec{b}\right|^2$)
- Even then, solution grossly magnifies statistical imprecision
- Use technique from math. stats.: Tikhonov regularization (Höcker and Kartvelishvili 1995)
- Expect true parton level distribution to be smooth

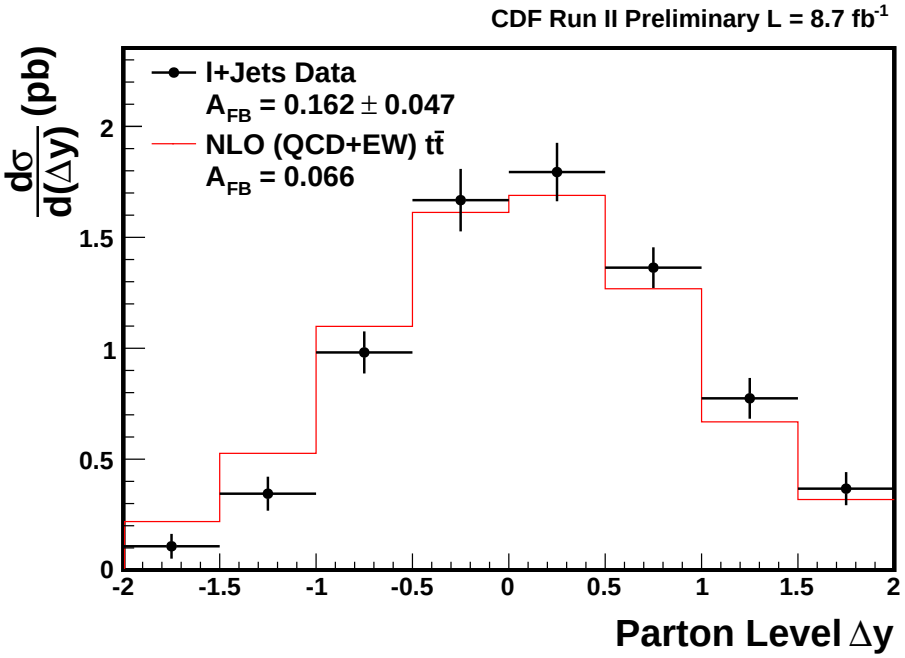


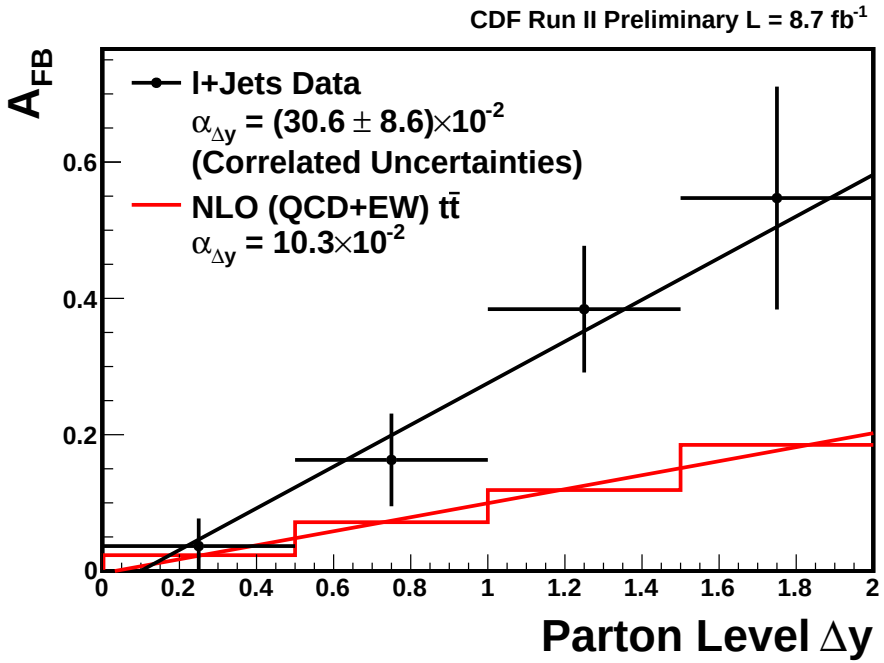
- Minimize $\left|S\vec{x} - \vec{b}\right|^2 + \tau \cdot |C\vec{x}|^2$
- C is matrix of second derivatives — encodes belief in smoothness
- Trade reduced statistical imprecision for small bias

CDF Run II Preliminary L = 8.7 fb^{-1}

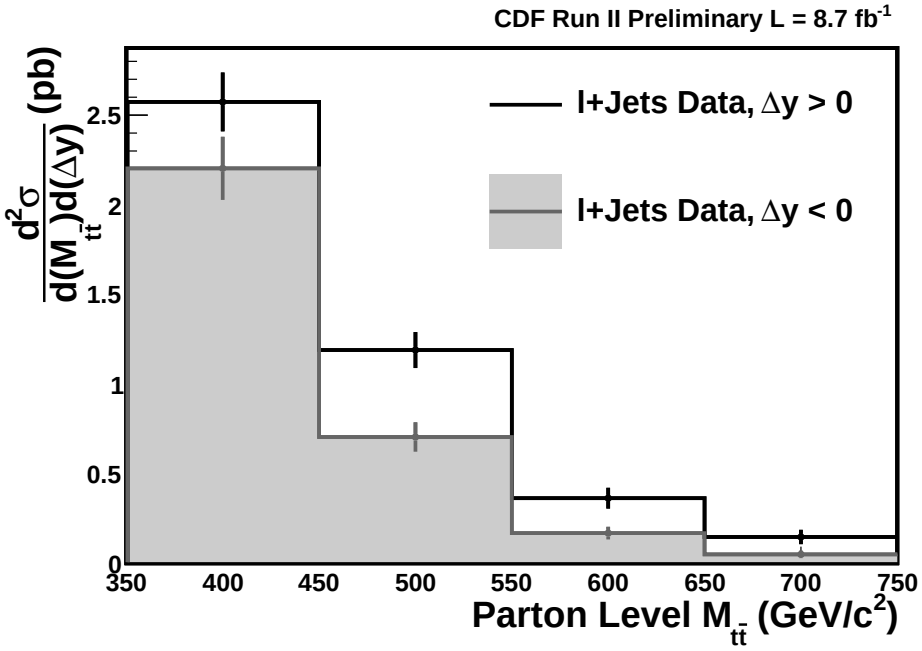
Source	Systematic Uncertainty
Background Shape	0.014
Background Normalization	0.011
Parton Showering	0.010
Jet Energy Scale	0.005
Initial and Final State Radiation	0.005
Color Reconnection	0.001
Parton Distribution Functions	0.001
Correction Procedure	0.003
Total Systematic Uncertainty	0.022
Statistical Uncertainty	0.041
Total Uncertainty	0.047

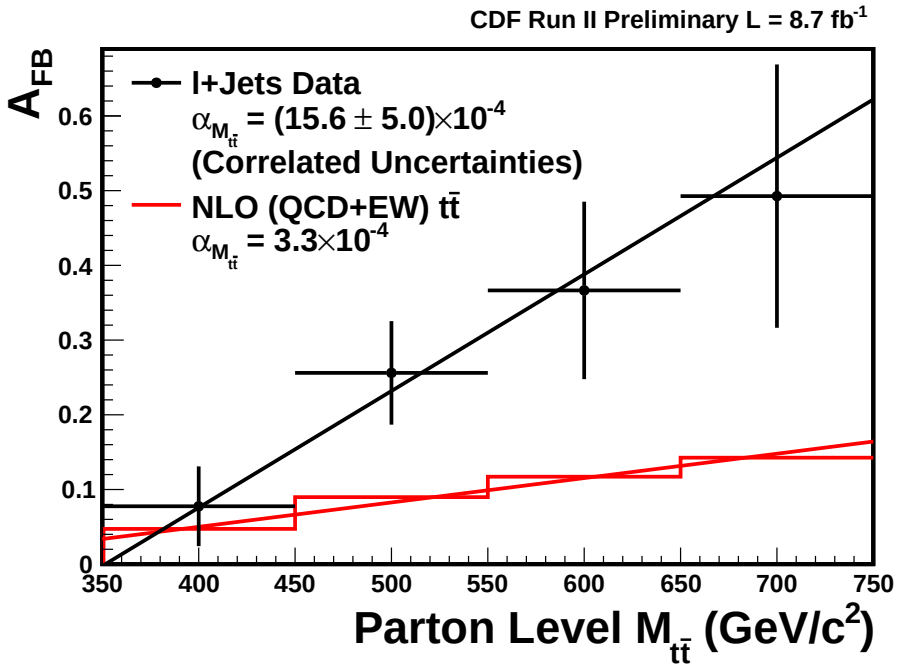
- Many sources of systematic uncertainty
- Statistical uncertainty dominates systematic uncertainty





- After correcting to parton level, get differential cross section $\frac{d\sigma}{d\Delta y}$
- From this, calculate A_{FB} in each bin of $|\Delta y|$
- Fit linear ansatz again
- Similar behavior as observed before correction
- Linear ansatz describes both data and SM well
- Slope not well described by SM



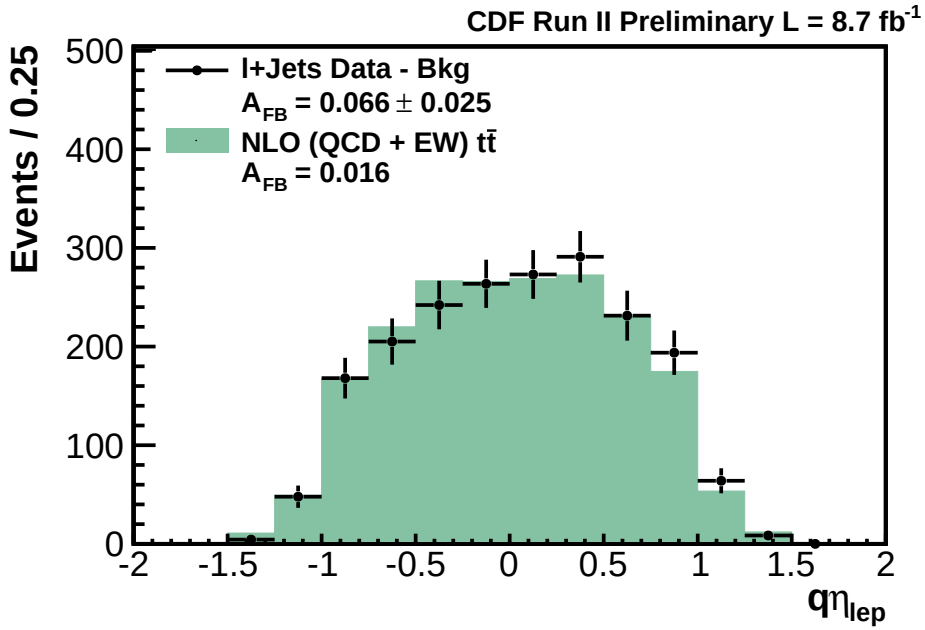


- Also correct differential cross sections in mass, $\frac{d\sigma}{dM_{t\bar{t}}}$, for forward and backward events
- Use this to calculate A_{FB} as a funtion of $M_{t\bar{t}}$
- Once again, linear ansatz describes data and SM, but slope not well described by SM.

Part VII

Additional Results

- Lepton pseudorapidity is independent of $t\bar{t}$ reconstruction
- Serves as a proxy for top quark rapidity
- Observation of an asymmetry in this variable helps validate $t\bar{t}$ A_{FB}
- $t\bar{t}$ A_{FB} is not an artifact of χ^2 fitter based $t\bar{t}$ reconstruction



CDF Run II Preliminary L = 8.7 fb^{-1}

	Data	NLO (QCD+EW) $t\bar{t}$
$M_{t\bar{t}}$	A_{FB} ($\pm$ [stat.+syst.])	A_{FB}
Inclusive	0.066 ± 0.025	0.016
$< 450\mathrm{GeV/c^2}$	0.037 ± 0.031	0.007
$\geq 450\mathrm{GeV/c^2}$	0.116 ± 0.042	0.032